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A REEXAMINATION OF THE AIRBLAST AND DEBRIS PRODUCED BY EXPLOSIONS INSIDE EARTH-COVERED IGLOOS

BY MICHAEL M. SWISDAK, JR.

RESEARCH AND TECHNOLOGY DEPARTMENT

28 JANUARY 1991

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NAVAL SURFACE WARFARE CENTER

Dahlgren, Virginia 22448-5000 • Silver Spring, Maryland 20903-5000

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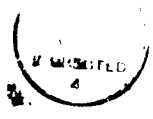

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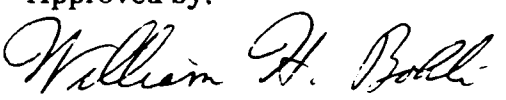
FOREWORD

This task was performed for the Department of Defense Explosives Safety Board (DDESB), Code KT, under the cognizance of Dr. J. M. Ward.

The mention of proprietary items or company names in this report is for technical information purposes only. No endorsement or criticism is intended.

Approved by:



WILLIAM H. BOHLI, Head
Energetic Materials Division

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CHAPTER 1

INTRODUCTION

At the request of the Department of Defense Explosives Safety Board (DDESB), the Naval Surface Warfare Center (NAVSWC) has conducted a review of the available airblast and fragmentation/debris information that was been produced by explosions within standard earth-covered, explosive storage magazines. The effort began during the 1990 fiscal year with the collection and collation of the data. During the current fiscal year (1991), the data have been compared with existing Department of Defense (DOD) explosives safety standards. The goals of this effort are to recommend possible changes to the standard (if needed) and to provide the best available prediction tools for both fragmentation/debris and airblast.

According to DOD-6055.9-STD,[1] standard earth-covered magazines are approved for all quantities of explosives up to 500,000 pounds (227,273 kg) net explosive weight. The standard defines five basic types of standard magazines: (1) reinforced concrete, arch-type magazines, (2) Navy-type magazines, (3) box-type A magazines, (4) earth-covered, corrugated steel, arch-type, and (5) earth-covered, circular composite arch. During the past 40 + years of testing, most or all of these types have been tested at one time or another. For the remainder of this report, the author will use the generic term "earth-covered igloo" when referring to all of these types. The United States Air Force has conducted many tests in what they have termed Modular or Hayman Igloos. These are also earth-covered but of a much simpler design. The data from these tests will be referred to as from "igloo structures" or from a modular igloo. The "igloo structures" have not been established as a standard type of magazine, therefore, they are only approved for storage up to 250,000 pounds.

The earliest documented testing of earth-covered igloos occurred shortly after World War II.[2,3] These tests were conducted at the Naval Proving Ground, Arco, Idaho. During the 1960s, tests were conducted at the Naval Ordnance Test Station (NOTS) (now, Naval Weapons Center, China Lake, CA).[4] These tests examined earth-covered, steel arch type magazine construction. Beginning in 1971, the DDESB began a series of tests call ESKIMO (ESKIMO is an acronym for Explosive Safety Knowledge IMprovement Operation).[5] These tests have continued through 1986 and constitute the source for the bulk of our knowledge regarding the blast and fragmentation/debris produced by explosions within these types of structures.[6-11] The Air Force igloo structure and modular igloo data have only recently been reported.[12-16]

CHAPTER 2

EVENTS CONSIDERED

Table 2-1 presents a summary of the events considered for this analysis. Many of them were not suitable for inclusion in the analyses that follow. The reasons for this range from the type of event (models, external shots, etc.) to the type of data collected (or not collected).

The ARCO tests[3] did not collect or consider fragmentation/debris data. The airblast data were collected with paper and foil gauges. As a result, these events are of little primary use to this study. A collateral test series to the ARCO tests used a series of scale models.[2] Again, the airblast was extremely crude and no debris data were collected. Because of the small scales involved and the fact that the donor charge was not scaled, these results are deemed inapplicable to the current study.

The NOTS Test Series[4] used a series of scale models to study the behavior of earth-covered, steel-arch magazines. Again, the scale was small and the donor charges were not scaled. As can be seen in the data comparison section, these events obviously constitute a different data set than the remainder of the igloo tests. One of the NOTS tests, NOTS 6, was a full-scale test and these results seem to belong to the same data set as the remainder of the full-scale igloo tests.

There have been seven ESKIMO tests since the start of that test series in 1971.[5-11] Of the seven, however, only three are applicable to this effort–ESKIMO I, ESKIMO III, and ESKIMO VI. The remainder did not have a donor charge detonating inside a magazine; rather, they were designed to study other aspects of igloo construction and safety.

In 1984, the U.S. Army conducted a series of tests to examine the minimum charge weight that could be contained within standard igloos.[17] Because of the nature of the tests, the charge weights and the loading densities were very low. The charge weights ranged from 12 to 150 pounds of TNT. In addition, there was a blast shield directly opposite the front door. Only limited low pressure (less than 2 psi) airblast data were recorded. Debris densities as a function of range and azimuth out the front were also recorded. Because of the nature of these events, the airblast data will not be considered in the general data base, but will be compared with the predictive methods derived in this study.

As part of the Air Force Buffered Storage Program, several tests were conducted inside both simulated and actual earth-covered igloos. The following criteria were applied to these tests in selecting which data to include in this study: (1) the Net Explosive Weight (NEW) had to be known; i.e., either the acceptor stack did not detonate (NEW = donor stack) or the acceptor detonated totally (NEW = donor plus acceptor) and (2) the structure had to have earth cover.

TABLE 2-1. EVENTS CONSIDERD FOR THIS STUDY

EVENT NAME	DATE	DONOR MAGAZINE TYPE	CHARGE SIZE/TYPE	COMMENTS	REFERENCE
ARCO 1	11/1/46	Earth-covered, reinforced concrete arch	930 MK 36 1000-pound bombs (500,340 pounds TNT)	(1) crude airblast (2) no debris data	ASESB TP 5
ARCO 2	11/8/46	Earth-covered, reinforced concrete arch	930 MK 36 1000-pound bombs (500,340 pounds TNT)	(1) crude airblast (2) no debris data	
ARCO 3	11/18/46	Earth-covered, reinforced concrete arch	465 MK 36 1000-pound bombs (250,170 pounds TNT)	(1) crude airblast (2) no debris data (3) double earth cover	
NOTS 1	1/17/62	Earth-covered, steel arch	8 AN-M-64A1 500-pound bombs (2,424 pounds TNT equivalent)	(1) model test (2) little debris data	NOTS TP 3843
NOTS 2	4/6/62	Earth-covered, steel arch	9 MK 54 350-pound depth bombs (2,611 pounds TNT equivalent)	(1) model test (2) little debris data	
NOTS 6	12/18/63	Earth-covered, steel arch	2106 cans of Composition B (111,039 pounds TNT equivalent)	(1) full scale (2) little debris data	
ESKIMO I	12/8/71	Earth-covered, steel arch	13,696 155 mm TNT-loaded projectiles (200,000 pounds TNT)	(1) debris data (2) good airblast data	NWC TP 5430
ESKIMO II	5/22/73	Open revetment	72 M117 bombs (24,000 pounds TNT equivalent)	(1) Not applicable	NWC TP 5557
ESKIMO III	6/12/74	Earth-covered, steel arch	916 M117 bombs (374,406 pounds TNT equivalent)	(1) airblast data (2) no debris data	NWC TP 5771
ESKIMO IV	Sep-75	Open, hemispherical stack	4,625 blocks of TNT (37,000 pounds TNT)	(1) Not applicable	NWC TP 5873
ESKIMO V	Aug-77	Open, hemispherical stack	9,376 blocks of TNT (75,000 pounds TNT)	(1) Not applicable	NWC TP 5873
ESKIMO VI	7/23/80	mass properties/geometry of earth-covered Type IIB	60 MK 16 torpedo warheads (51,300 pounds TNT equivalent)	(1) 1/2-scale model (2) airblast data (3) no debris data	NCEL TR-889
ESKIMO VII-IIA roof	9/5/85	FOAMHEST	Primacord	(1) Not applicable	NCEL TM 51-86-26
ESKIMOVII-IIB doors	9/12/85	Open, hemispherical stack	1,702 blocks of TNT (13,616 pounds TNT)	(1) Not applicable	
HASTINGS IGLOO	1984	Earth-covered, reinforced concrete arch	8-pound TNT blocks 12-150 pounds of TNT	(1) Low loading densities (2) airblast data (3) debris data	ARBRL-03356
MK82-1	2/5/87	Earth-covered igloo-bunker	180 MK82 bombs (36,600 pounds TNT equivalent)	(1) No debris (2) Impulse incorrect	MMW-TR-87-C77865A
MK82-2	5/7/87	Earth-covered igloo-bunker	270 MK82 bombs (54,890 pounds TNT equivalent)	(1) No debris (2) Impulse incorrect	MMW-TR-87-C77865A
MK82-3	11/4/87	Earth-covered igloo-bunker	312 MK82 bombs (63,430 pounds TNT equivalent)	(1) No debris (2) Impulse incorrect	MMW-TR-87-C77865A
MK82-4	12/18/87	Earth-covered igloo-bunker	312 MK82 bombs (63,430 pounds TNT equivalent)	(1) No debris (2) Impulse incorrect	MMW-TR-87-C77865A
MK84-13	8/29/86	Earth-Covered reinforced concrete arch	128 MK 84 bombs (129,430 pounds TNT equivalent)	(1) No debris (2) Impulse incorrect	MMW-TR-87-50102AC
MK84-15	11/14/86	Earth-covered igloo bunker	96 MK84 bombs (96,620 pounds TNT equivalent)	(1) No debris (2) Impulse incorrect	MMW-TR-87-50102AC
MK84-17	6/24/87	Earth-covered igloo bunker	48 MK84 bombs (48,535 pounds TNT equivalent)	(1) No debris (2) Impulse incorrect	MMW-TR-87-50102AC
MK84-18	8/12/87	Earth-covered igloo bunker	64 MK84 bombs (64,714 pounds TNT equivalent)	(1) No debris (2) Impulse incorrect	MMW-TR-87-50102AC
MK84-19	9/23/87	Earth-covered igloo bunker	64 MK84 bombs (64,714 pounds TNT equivalent)	(1) No debris (2) Impulse incorrect	MMW-TR-87-50102AC
MODULAR IGLOO	11/18/88	Earth-Covered Hayman igloo	450,450 pounds Flake Composition B (500,000 pounds TNT equivalent)	(1) No debris (2) Impulse incorrect	MMW-TR-88-71002AC

CHAPTER 3

DEBRIS/FRAGMENTATION

Only three events collected debris information that might be considered useful–ESKIMO I, ESKIMO VI, and HASTINGS IGLOO. Of these three, the ESKIMO I event collected detailed fragmentation/debris data over a full 360° azimuth. All the debris information collected is presented in Appendix A. ESKIMO VI presented only descriptive information, so no quantitative determinations can be drawn from it.

DEFINITIONS AND CRITERIA

The DDESB defines a hazardous fragment density as "A density of hazardous fragments exceeding one per 600 sq ft. (55.7 m^2)."[1] A hazardous fragment is defined as "one having an impact energy of 58 ft-lb (79 Joules) or greater." Recent interpretations by the Secretariat of the DDESB have taken the 600 ft^2 to be measured trajectory-normal as opposed to ground surface pickup. Procedures for the standardization of the analyses of debris have also been produced.[18] These standardized procedures have been used to reexamine the debris data collected on both ESKIMO I and the HASTINGS IGLOO tests.

ESKIMO I

Both magnetic and hand pickup were used on this test. Three 5° sectors (off the front, side, and rear of the structure) were surveyed in and cleared of vegetation and debris before the test. These sectors were collected by magnetic pickup. In addition, foot search and hand pickup were conducted in selected 100 ft x 100 ft areas. These additional areas were selected to supplement the data derived from the magnetic pickup as well as to extend the collection areas into locations not accessible to the truck-mounted magnet. For this test, calculations indicated that for a free-falling fragment or piece of debris to be hazardous, it would have to have a weight of at least 0.28 pound.

The data were presented in graphs in terms of debris densities as a function of range for various debris weights (≥0.125 pound, ≥0.28 pound, ≥1.0 pound). For this analysis, the density-range data were read off the graphs for the ≥0.28 pound information. These data were then converted to pseudo-trajectory normal densities and analyzed according to the procedures of Reference 18. Figures 3-1 through 3-5 present the results. Remember that the hazardous fragment range is the range at which a least squares exponential fit through the pseudo-trajectory normal data reaches a value of 1. Also shown on each graph is the 90 percent confidence interval for the hazardous debris range.

Thus, out the front of the igloo on this test the hazardous fragment range was 3857 feet; off the side it was 2743 feet; out the rear it was 2376 feet. These correspond to scaled ranges of 66.0, 46.9, and 40.6 ft/lb$^{1/3}$, respectively.

HASTINGS IGLOO

Significant debris data were collected on four of the HASTINGS IGLOO tests, the 60-, 80-, 100-, and 150-pound tests. Fragment density distributions at distances less than 175 feet (53 meters) were not used due to the masking effect of a blast shield in front of the structure.

It is probably appropriate to describe the test structures before the results are presented. The site was part of an abandoned Navy Ammunition Depot that was constructed during World War II. All of the igloos exhibited structural failures in the form of hairline cracks in the sidewalls, arch crest, backwall, and headwall. Erosion of the earth cover was observed in many cases due to a lack of maintenance. The magazine headwalls faced an earth-backed concrete blast shield. The distance between the vertical headwalls and the blast shields varied between 12 feet at the base and 15 feet at the top.

The debris results are summarized in Figures 3-6 to 3-9. On each test, debris was collected in three separate zones: 0° to 5°, 5° to 10°, and 10° to 45°. The hazardous fragment range (i.e., the range at which the hazardous fragment density becomes 1) extended to significant scaled distances out the front. The unscaled ranges are shown on each graph. In addition, the 90 percent confidence interval is shown for each of the ranges. These ranges correspond to scaled distances of 112.9, 143.7, 103.0, and 150.2 ft/lb$^{1/3}$. These scaled ranges are much greater that those measured on ESKIMO I. They may be affected by the poor condition of the structures existing at the time of the test. Moreover, the loading densities (charge weight/internal volume of structure) used on these tests were quite low; thus, the roof and sides of the structure did not fail–channeling the debris out the front. The range of hazardous fragments is less than 670 feet for less than 100 pounds and the maximum range is less than 700 feet for 150 pounds.

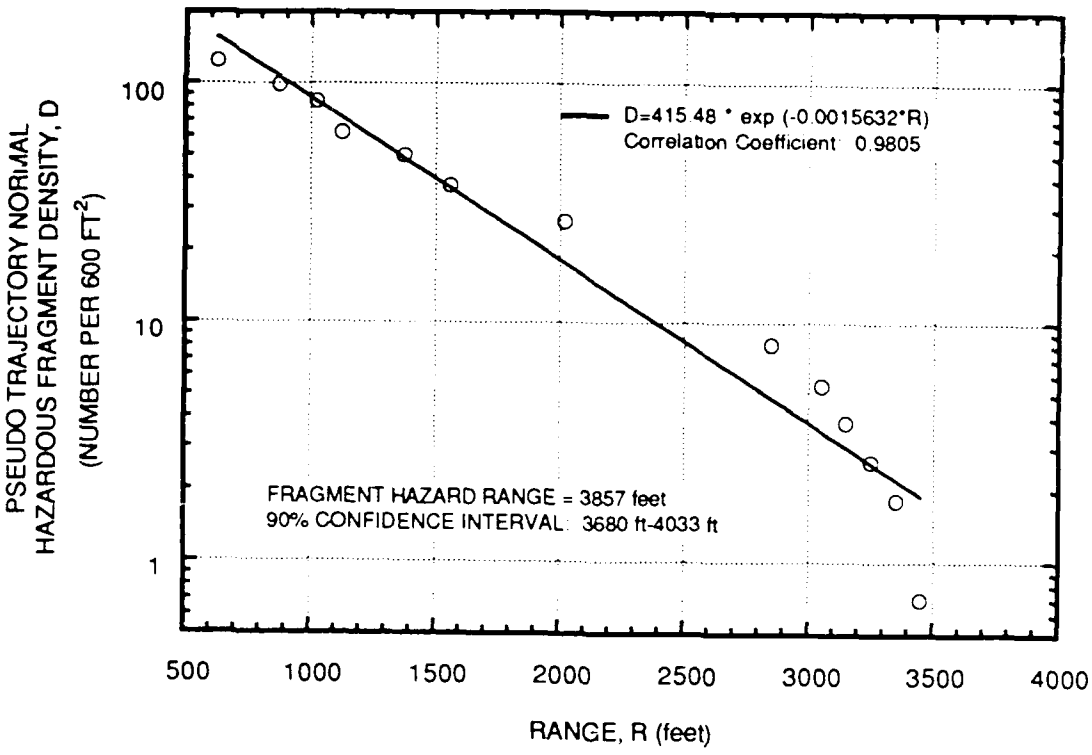

FIGURE 3-1. ESKIMO I: HAZARDOUS FRAGMENT DENSITY VERSUS RANGE (FRONT)

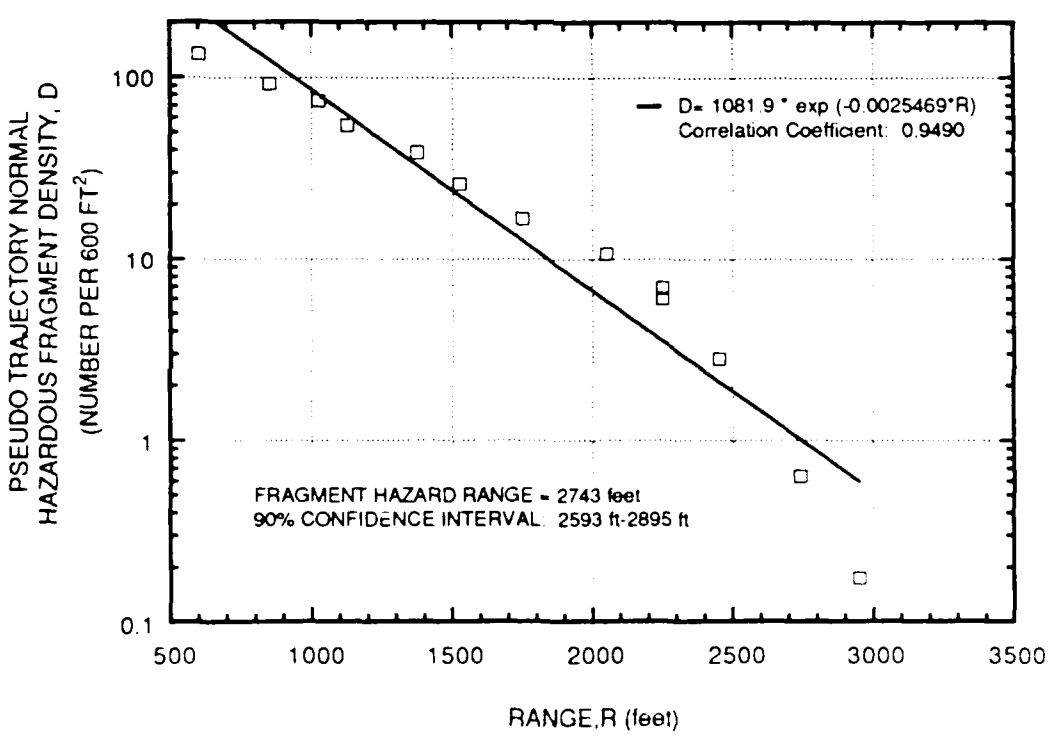

FIGURE 3-2. ESKIMO I: HAZARDOUS FRAGMENT DENSITY VERSUS RANGE (SIDE)

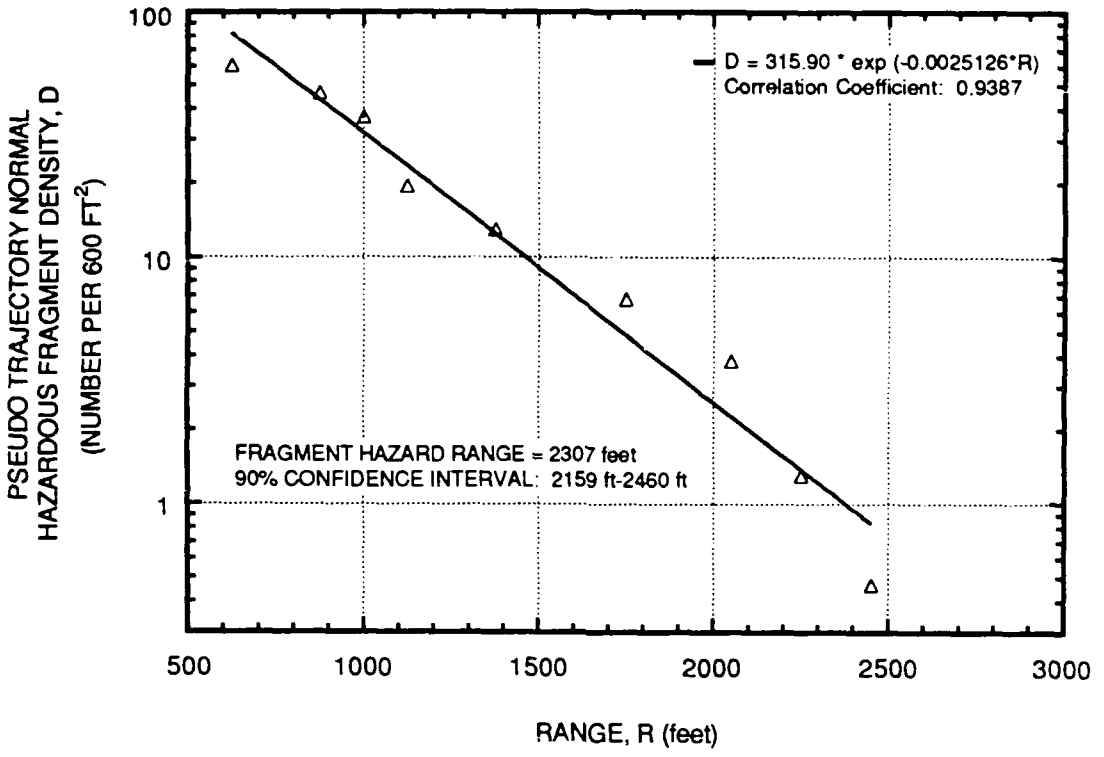

FIGURE 3-3. ESKIMO I: HAZARDOUS FRAGMENT DENSITY VERSUS RANGE (REAR)

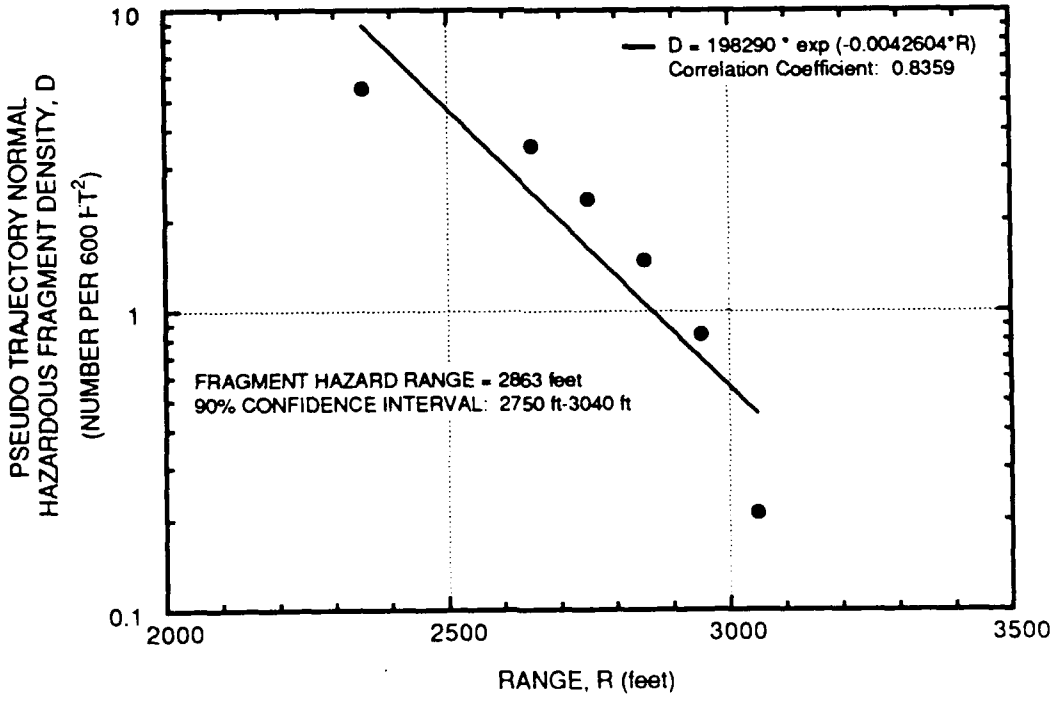

FIGURE 3-4. ESKIMO I: HAZARDOUS FRAGMENT DENSITY VERSUS RANGE (FRONT/SIDE DIAGONAL)

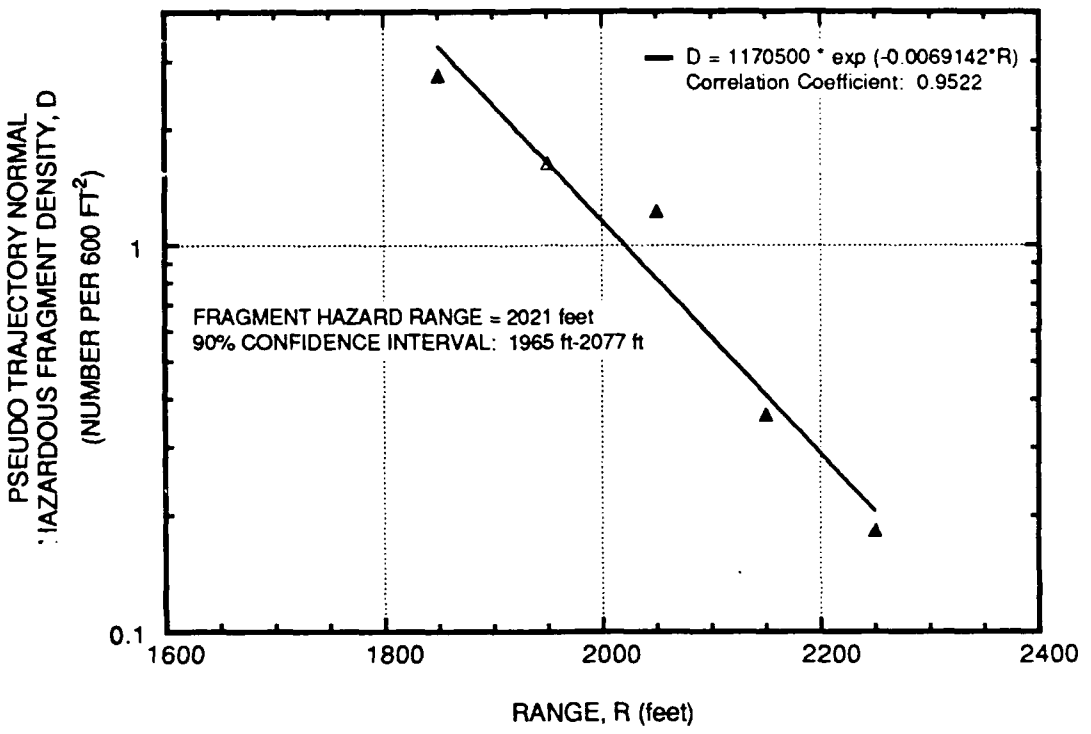

FIGURE 3-5. ESKIMO I: HAZARDOUS FRAGMENT DENSITY VERSUS RANGE (REAR/SIDE DIAGONAL)

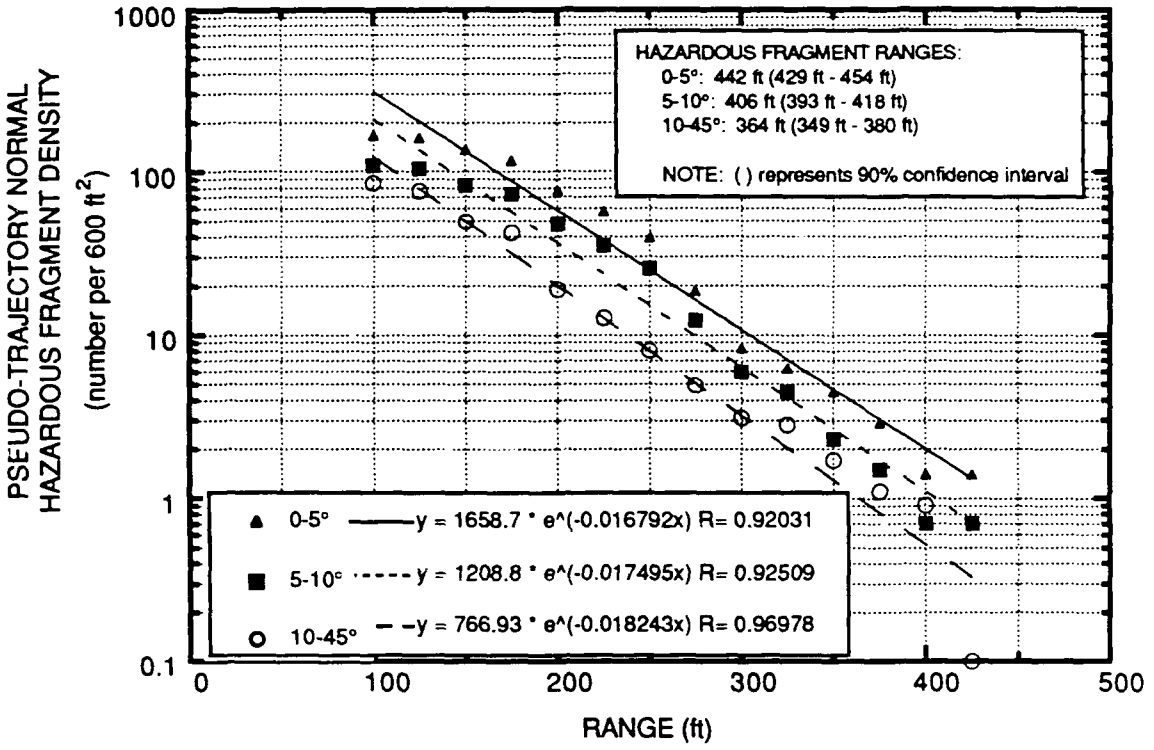

FIGURE 3-6. HASTINGS IGLOO–60-POUND TEST HAZARDOUS FRAGMENT DENSITY VERSUS RANGE

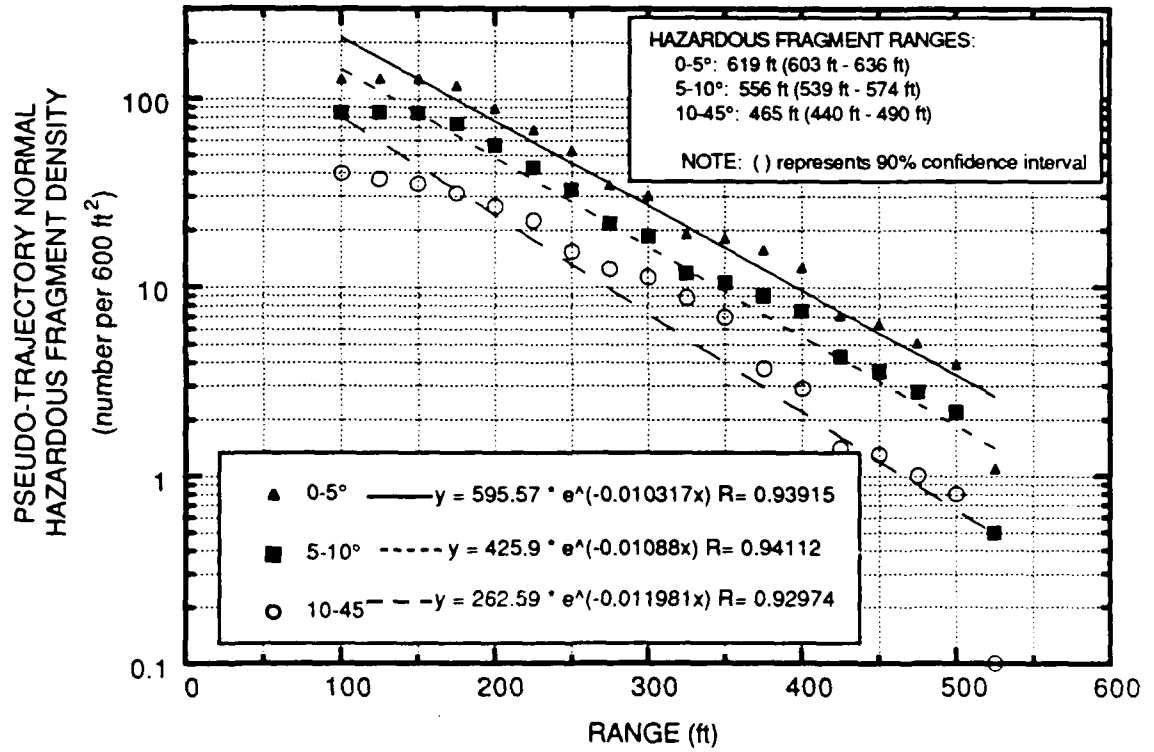

FIGURE 3-7. HASTINGS IGLOO–80-POUND TEST HAZARDOUS FRAGMENT DENSITY VERSUS RANGE

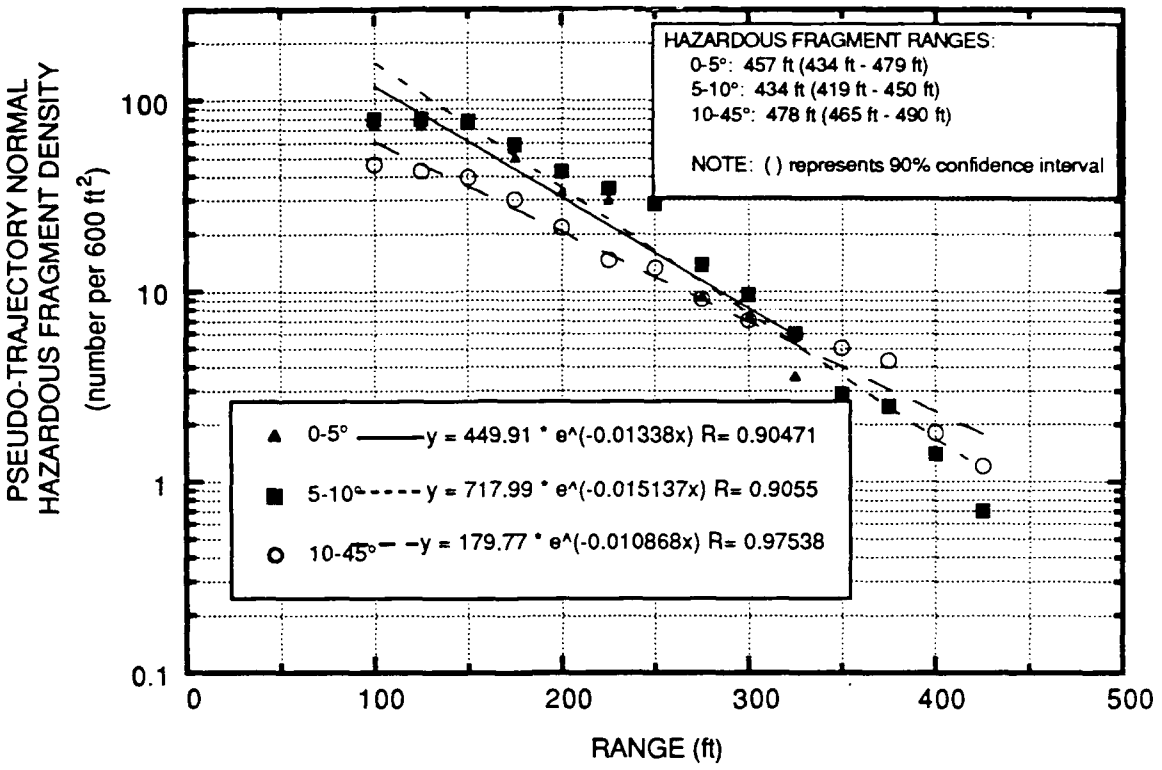

FIGURE 3-8. HASTINGS IGLOO–100-POUND TEST HAZARDOUS FRAGMENT DENSITY VERSUS RANGE

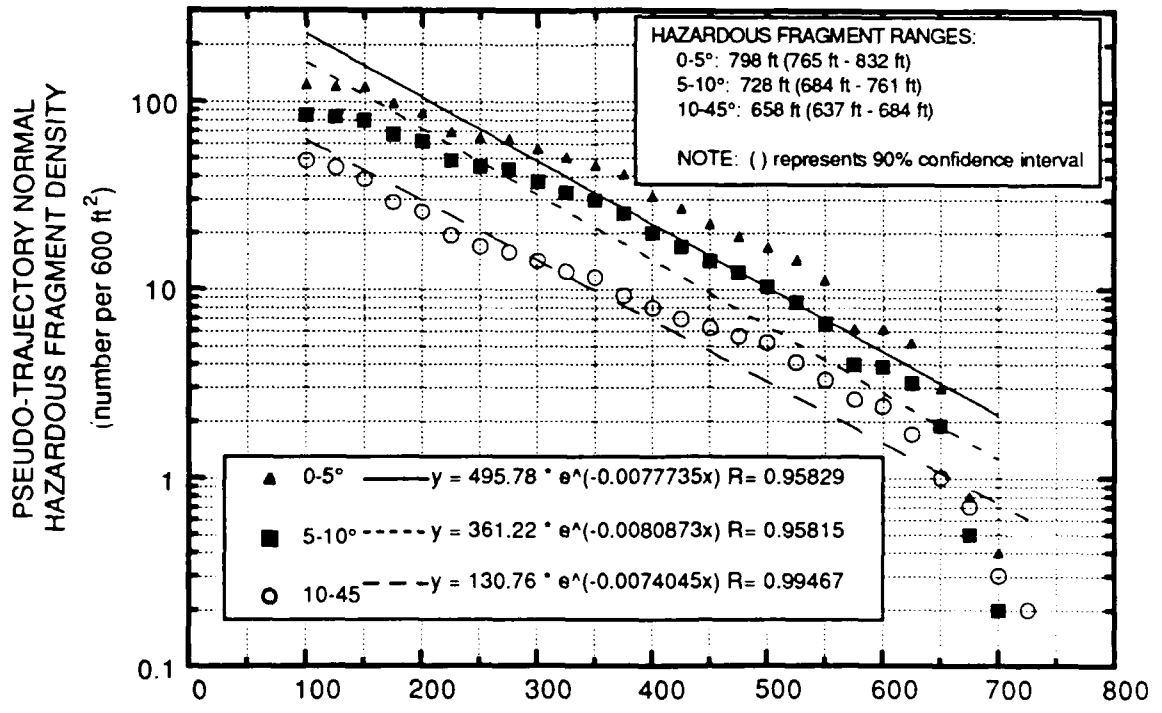

FIGURE 3-9. HASTINGS IGLOO–150-POUND TEST HAZARDOUS FRAGMENT DENSITY VERSUS RANGE

CHAPTER 4

AIRBLAST

Airblast information has been collected on almost all of these events. Unfortunately, the coverage has been somewhat spotty. Moreover, the quality of the far-field data (below 10 psi) has ranged from barely adequate to totally lacking. All of the airblast data that has been obtained is presented in tabular form in Appendix B. Only the following events will be analyzed in detail: NOTS 6, ESKIMO I, ESKIMO III, and ESKIMO VI.

DEFINITIONS AND CRITERIA

DOD 6055.9-STD[1] and NATO guidelines define several acceptable exposures which might be applied to aboveground magazines. These are:

1. Permissible exposure to airblast overpressure–barricading required: $9W^{1/3}$ (11.7 psi)
2. Unbarricaded aboveground magazine distance: $11W^{1/3}$ (8.0 psi)
3. Unbarricaded intraline distance: $18W^{1/3}$ (3.5 psi)
4. NATO Workshop distance: $20W^{1/3}$ (3.0 psi)
5. Public Traffic Route Distance–$W < 100{,}000$ pounds: $24W^{1/3}$ (2.3 psi)
6. Inhabited Building Distance–Rear of earth covered magazine–$W < 100{,}000$ pounds: $25W^{1/3}$ (2.2 psi)
7. Public Traffic Route Distance–$W > 250{,}000$ pounds: $30W^{1/3}$ (1.7 psi)
8. Inhabited Building Distance–Front and Side of earth covered magazine–$W < 100{,}000$ pounds: $35W^{1/3}$ (1.4 psi)
9. NATO Public Traffic Route: $37.5W^{1/3}$ (1.3 psi)
10. Inhabited Building Distance–$W < 100{,}000$ pounds: $40W^{1/3}$ (1.2 psi)
11. Inhabited Building Distance–$W > 250{,}000$ pounds: $50W^{1/3}$ (0.9 psi)
12. NATO Inhabited Building Distance: $58.7W^{1/3}$ (0.725 psi or 50 mbar)
13. NATO Twice Inhabited Building Distance: $115W^{1/3}$ (0.29 psi or 20 mbar)

The scaled distances which these criteria refer to are directly related to peak overpressure. The relationship is based on the Kingery compilation of surface burst, hemispherical TNT data,[19,20] referred to hereafter as the Kingery TNT standard. Table 4-1 presents an excerpt of the data contained in this standard. This will form the basis for all the airblast comparisons that will be performed later.

Figures 4-1 through 4-8 present the airblast results measured on the following events: NOTS 6, ESKIMO I, ESKIMO III, and ESKIMO VI. The data presented in Appendix B have been scaled to sea level conditions for each event. In addition, the curve marked standard on each graph is the Kingery hemispherical standard curve for the TNT weight of the event. Least square curves have been fitted to each of these data sets, so that the ranges to various pressure levels can be computed. This curve fit information is presented in Table 4-2.

The Air Force simulated igloo (buffered storage) and modular igloo data are being considered separately since they do not represent an, as yet, approved magazine design. This data is also presented in Appendix B. There seems to be a problem with the impulse information. For this reason, none of these data will be analyzed or discussed further.

Instead of discussing each test within the buffered storage and modular igloo data sets, the Appendix B information has been scaled to sea level conditions and to a charge weight of 1 pound. These results are presented in Figures 4-9 and 4-10 for the front and side directions. Also shown on each graph is the Kingery hemispherical standard. Least square curves have also been fitted to this data set so that the ranges to various pressure levels can be computed. This information is presented in Table 4-2.

Using the information presented in Table 4-2, ranges and pressures can be calculated for each of the potential criteria presented above. This will then allow direct comparison for each of the standards. These results are presented in Table 4-3. Only the data for ESKIMO VI show any violation of the criteria. In this case, the numbers are so close to the standard that there is no statistical difference between the least square curve fit value and the standard itself. Thus, based on this information, the standard appears to be safety conservative.

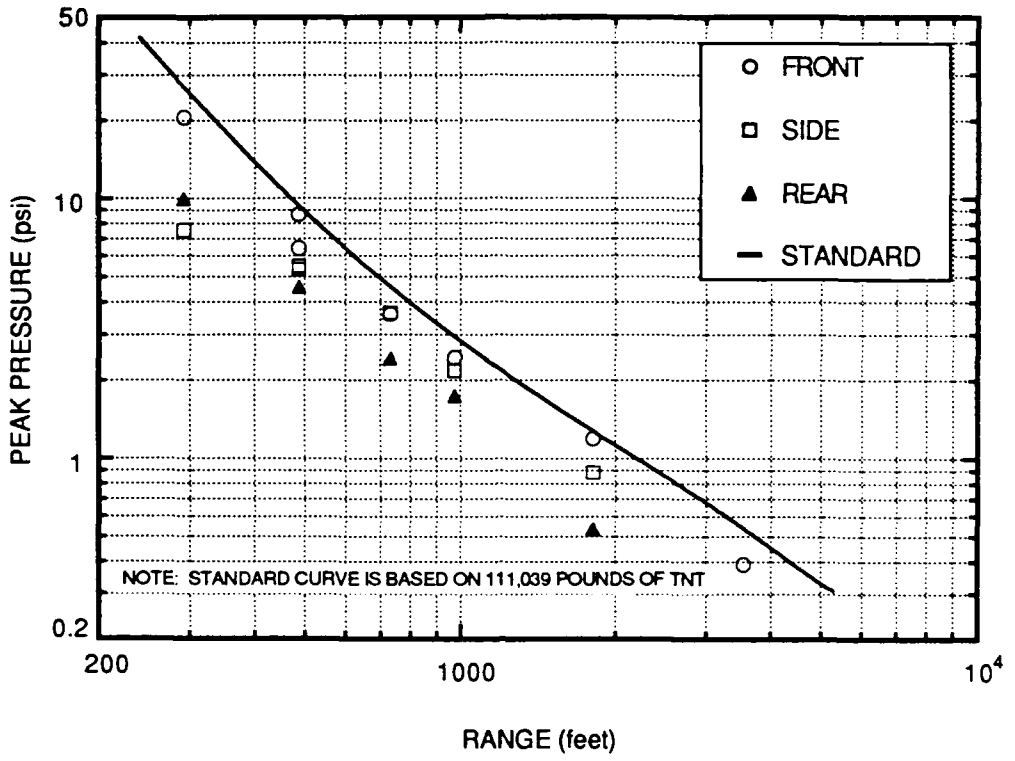

FIGURE 4-1. NOTS 6: PRESSURE-DISTANCE DATA SCALED TO SEA LEVEL CONDITIONS

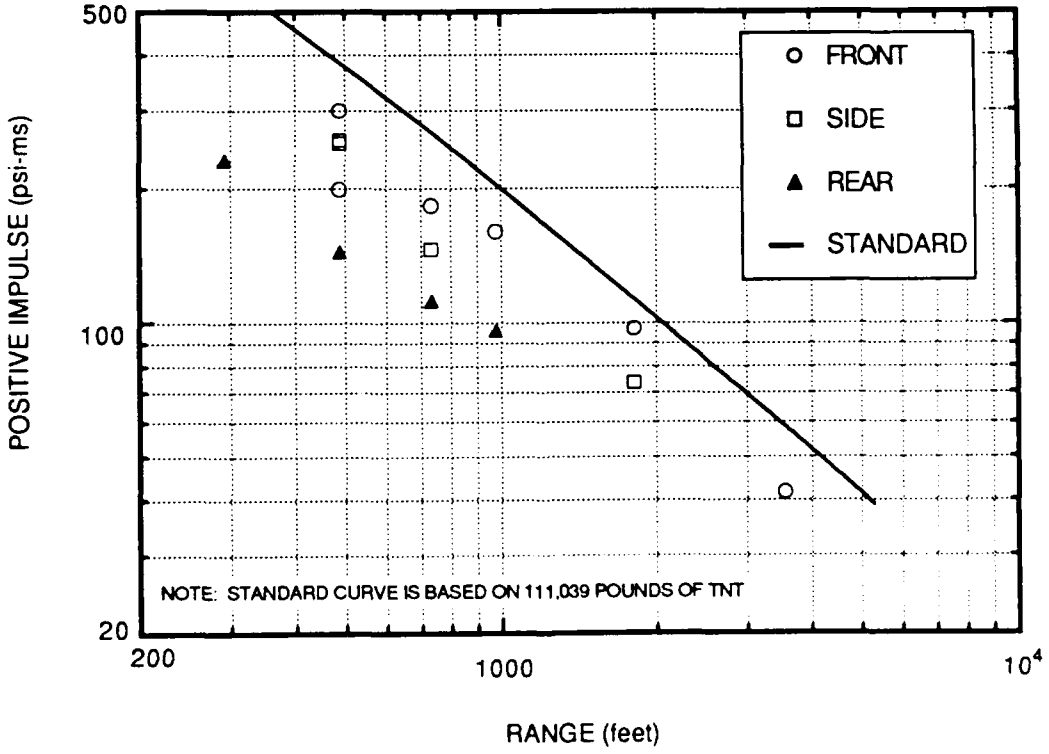

FIGURE 4-2. NOTS 6: IMPULSE-DISTANCE DATA SCALED TO SEA LEVEL CONDITIONS

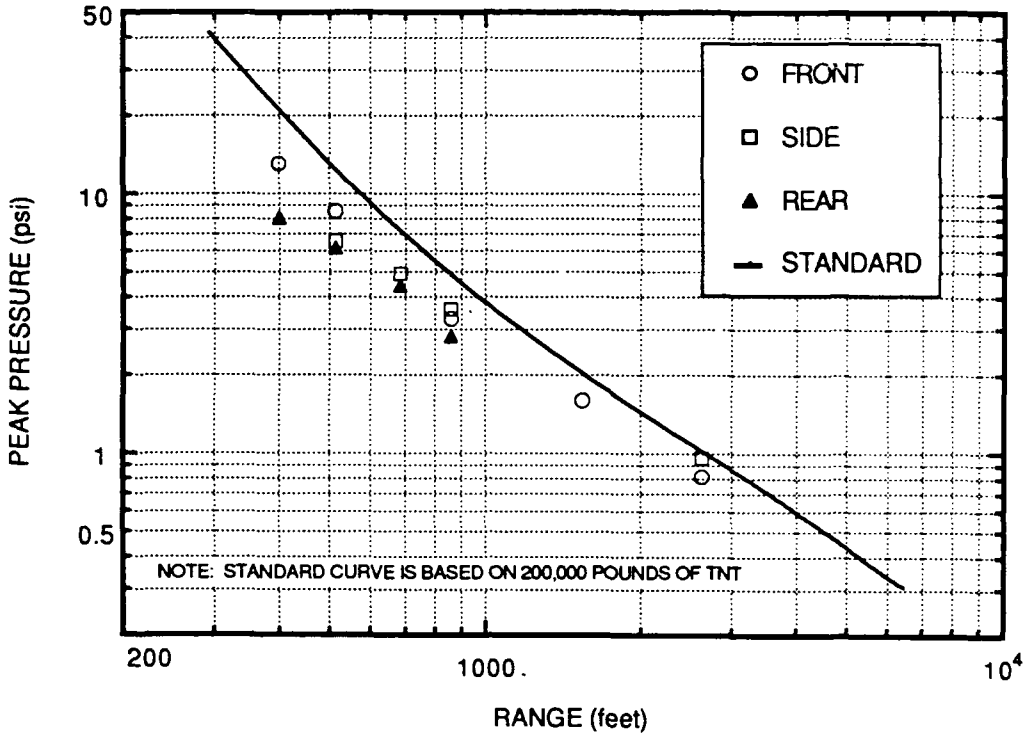

FIGURE 4-3. ESKIMO I: PRESSURE-DISTANCE DATA SCALED TO SEA LEVEL CONDITIONS

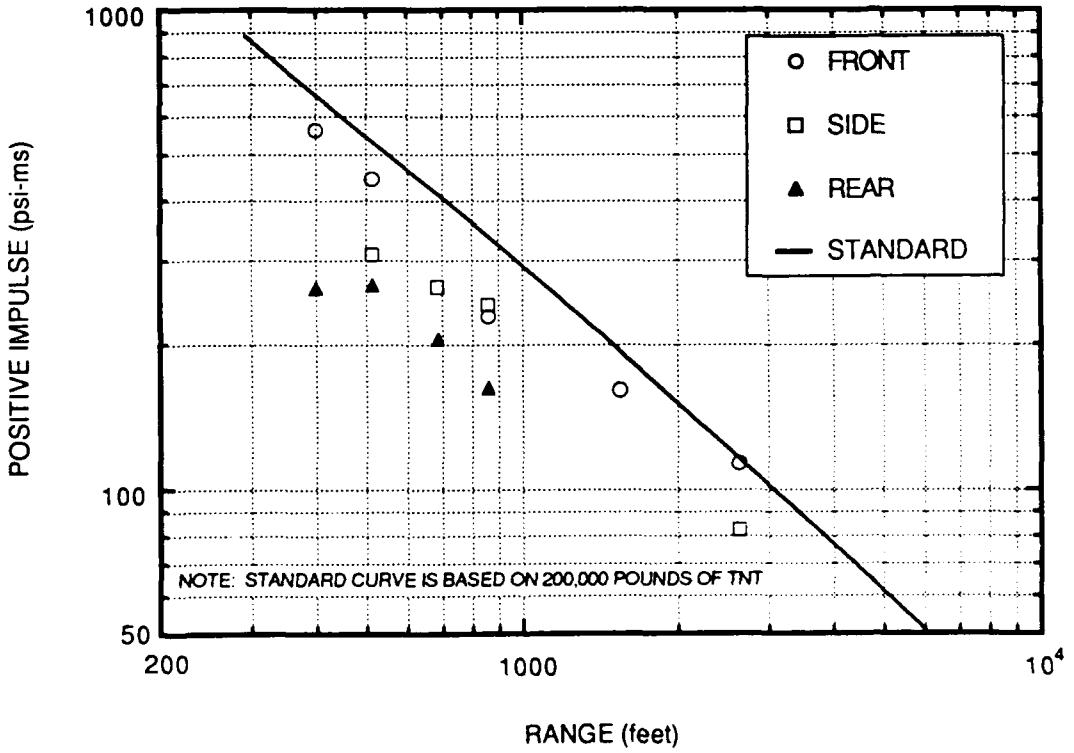

FIGURE 4-4. ESKIMO I: IMPULSE-DISTANCE DATA SCALED TO SEA LEVEL CONDITIONS

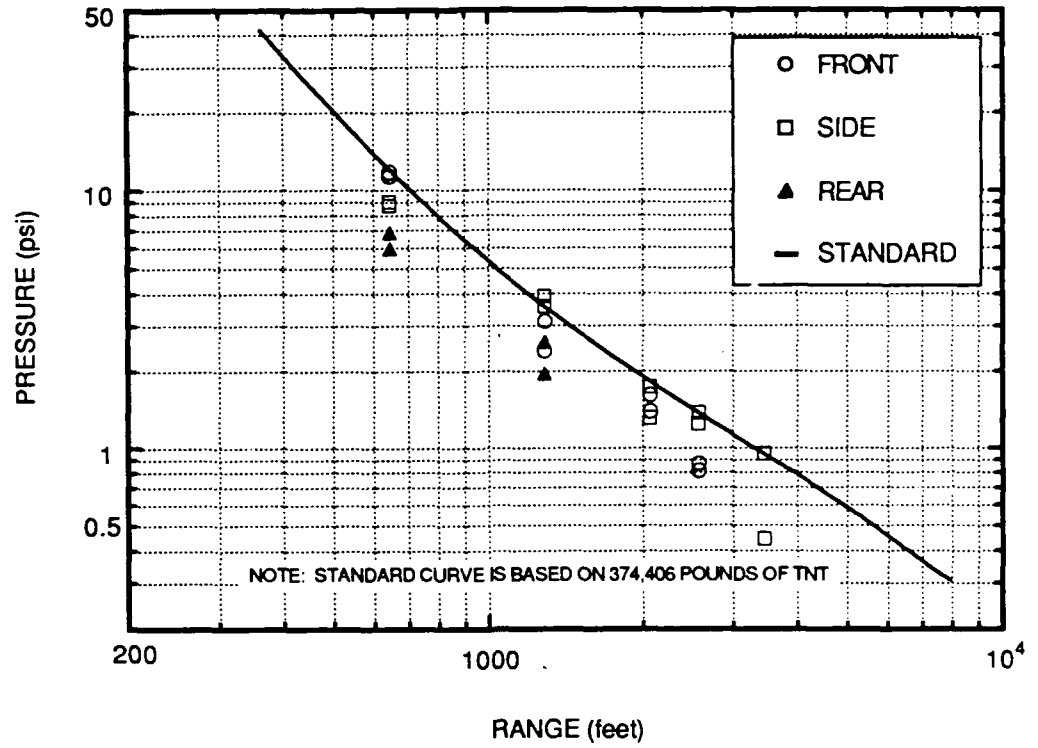

FIGURE 4-5. ESKIMO III: PRESSURE-DISTANCE DATA SCALED TO SEA LEVEL CONDITIONS

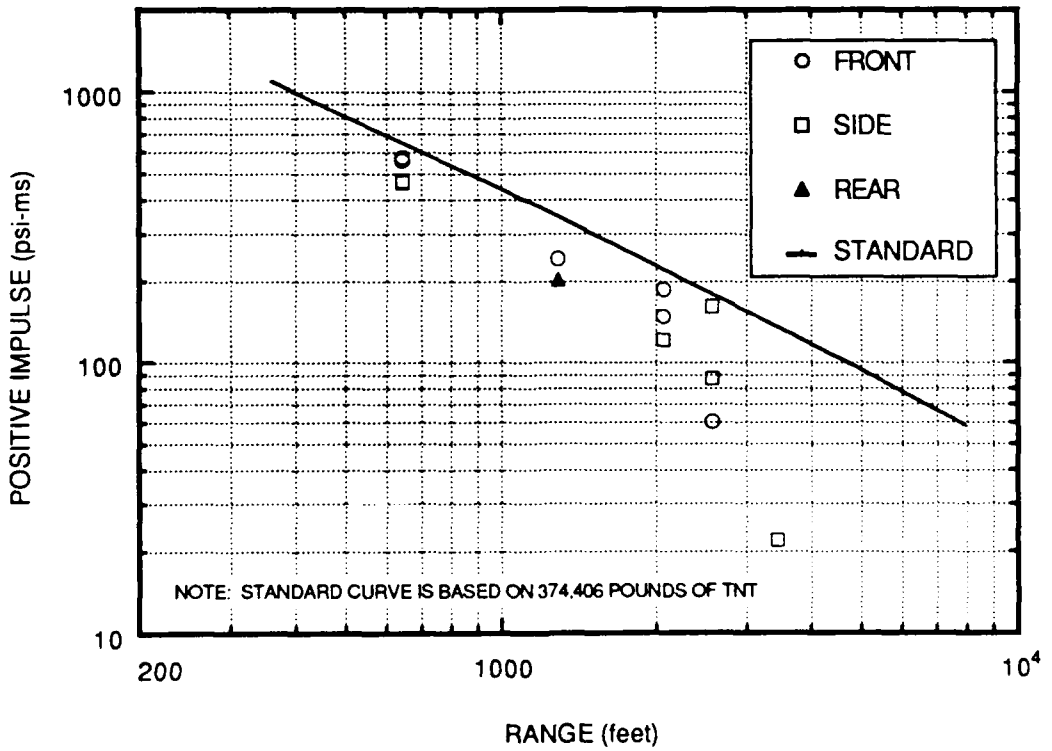

FIGURE 4-6. ESKIMO III: IMPULSE-DISTANCE DATA SCALED TO SEA LEVEL CONDITIONS

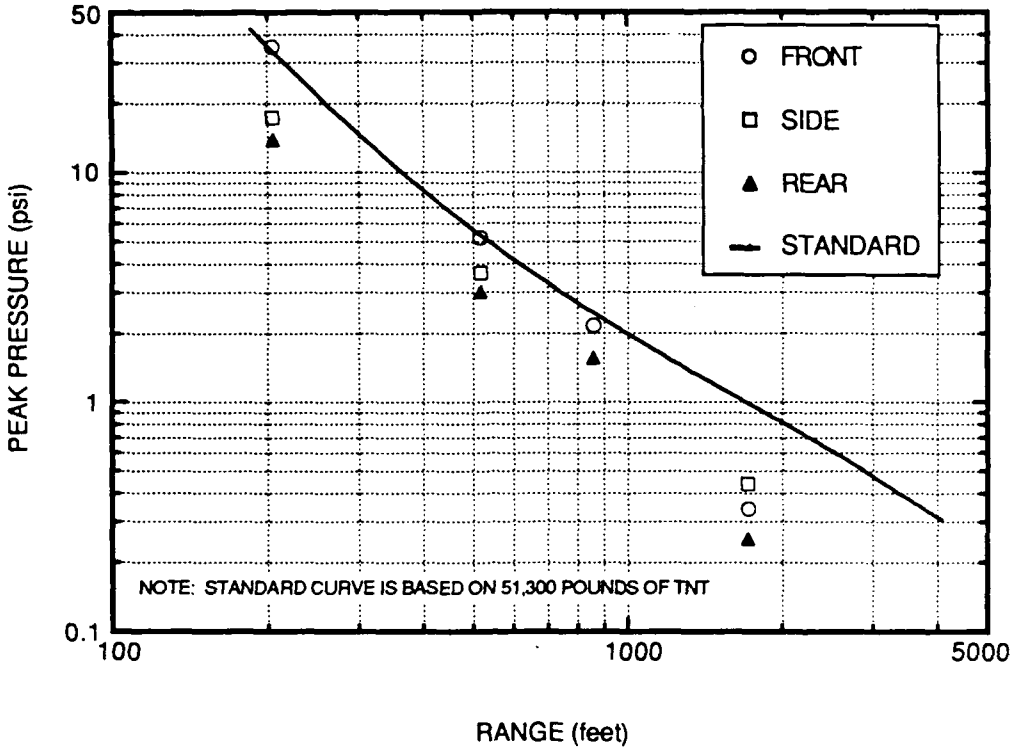

FIGURE 4-7. ESKIMO VI: PRESSURE-DISTANCE DATA SCALED TO SEA LEVEL CONDITIONS

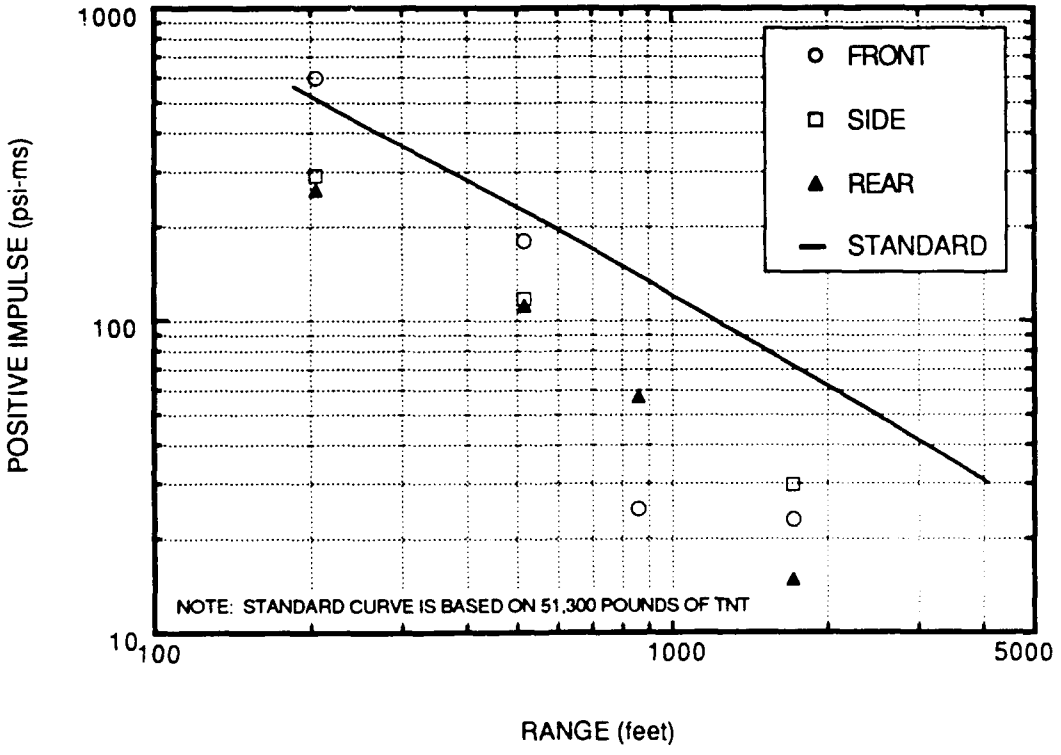

FIGURE 4-8. ESKIMO VI: IMPULSE-DISTANCE DATA SCALED TO SEA LEVEL CONDITIONS

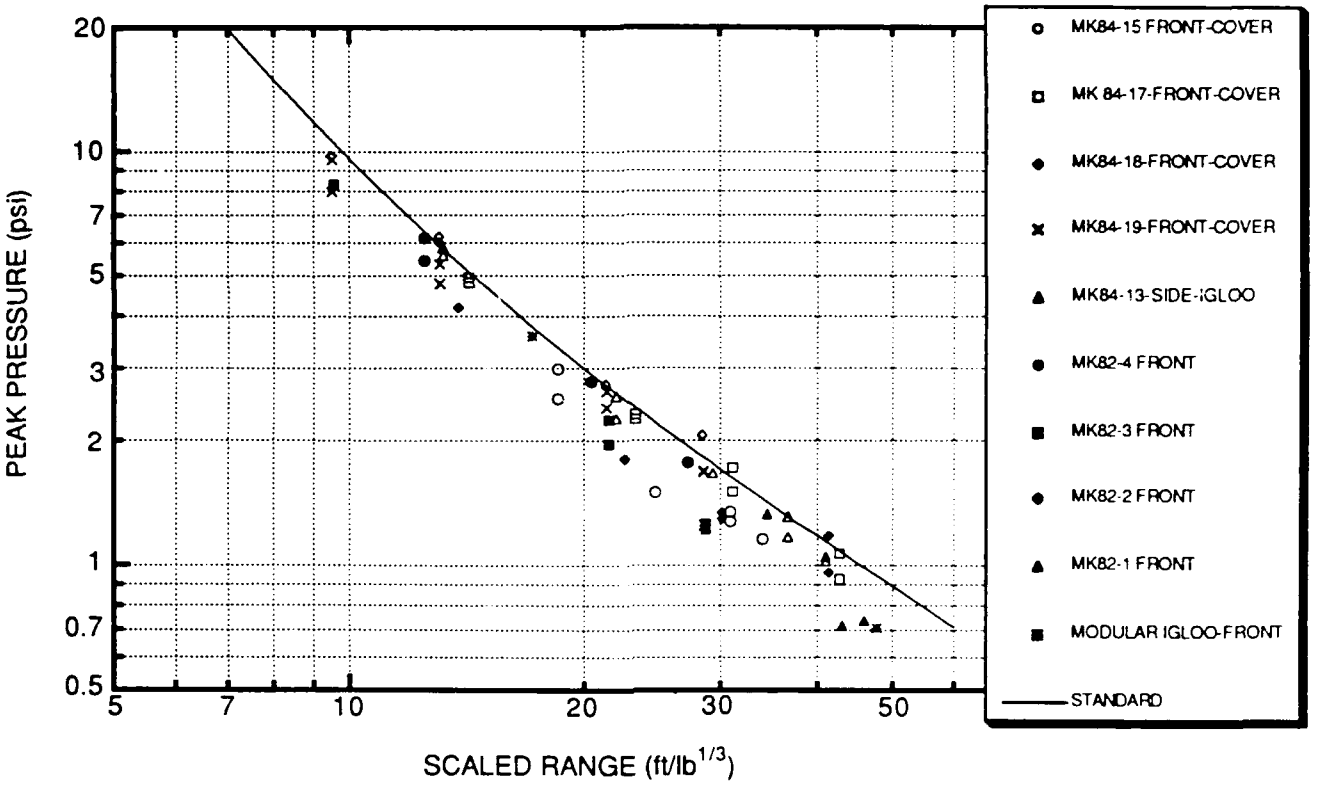

FIGURE 4-9. BUFFERED STORAGE AND MODULAR IGLOO RESULTS PRESSURE-DISTANCE DATA–FRONT SCALED TO SEA LEVEL CONDITIONS

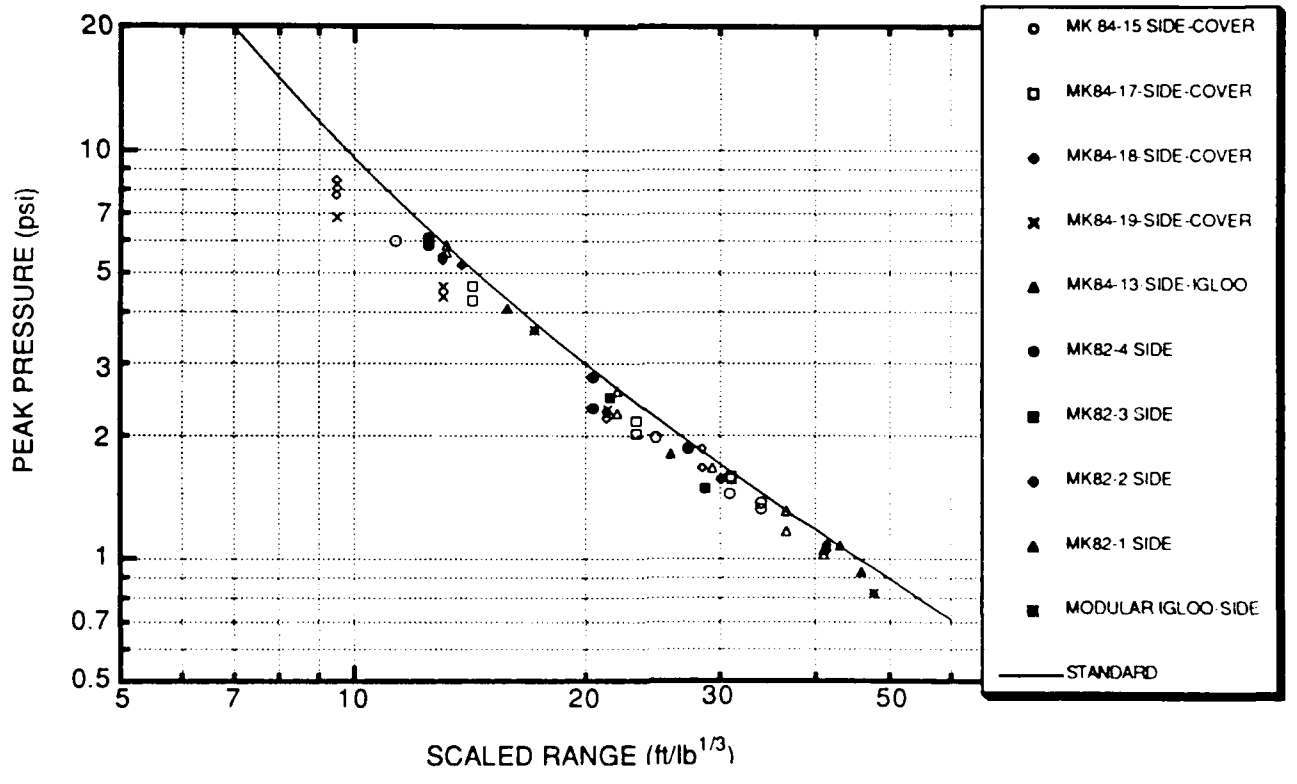

FIGURE 4-10. BUFFERED STORAGE AND MODULAR IGLOO RESULTS PRESSURE-DISTANCE DATA–SIDE SCALED TO SEA LEVEL CONDITIONS

TABLE 4-1. KINGERY HEMISPHERICAL STANDARD

SCALED DISTANCE (ft/lb^1/3)	PEAK PRESSURE (psi)	POSITIVE IMPULSE (psi-ms)/lb^1/3
6.0	27.74	12.73
7.0	19.78	11.07
8.0	14.92	9.84
9.0	11.75	8.88
10.0	9.56	8.10
11.0	8.00	7.45
12.0	6.83	6.90
13.0	5.94	6.42
14.0	5.23	6.01
15.0	4.67	5.64
16.0	4.21	5.32
17.0	3.82	5.03
18.0	3.50	4.77
19.0	3.22	4.53
20.0	2.99	4.31
21.0	2.78	4.12
22.0	2.60	3.94
23.0	2.44	3.77
24.0	2.30	3.62
25.0	2.17	3.48
26.0	2.06	3.35
27.0	1.96	3.23
28.0	1.86	3.12
29.0	1.78	3.02
30.0	1.70	2.92
32.5	1.53	2.70
35.0	1.39	2.52
37.5	1.27	2.35
40.0	1.18	2.21
42.5	1.09	2.09
45.0	1.01	1.97
47.5	0.95	1.87
50.0	0.89	1.78
55.0	0.79	1.62
60.0	0.71	1.49
65.0	0.63	1.38
70.0	0.57	1.28
75.0	0.52	1.19
80.0	0.48	1.12
85.0	0.44	1.05
90.0	0.40	0.99
100.0	0.35	0.89
110.0	0.30	0.81
120.0	0.27	0.74
130.0	0.24	0.68

REFERENCES:

(1) ARBRL-TR-02555
(2) BRL Report 1344

TABLE 4-2. LEAST SQUARES FIT COEFFICIENTS–PRESSURE-DISTANCE

EVENT	DIRECTION	A	B	CORRELATION COEFFICIENT
NOTS 6	FRONT	98,219	-1.5264	0.9882
	SIDE	9,033	-1.2120	0.9643
	REAR	80,640	-1.5793	0.9996
ESKIMO I	FRONT	81,631	-1.4742	0.9970
	SIDE	10,904	-1.1856	0.9985
	REAR	26,789	-1.3466	0.9917
ESKIMO III	FRONT	1,492,300	-1.8279	0.9973
	SIDE	196,630	-1.5357	0.9947
	REAR	108,600	-1.5064	0.9822
ESKIMO 6	FRONT	3,402,700	-2.1452	0.9999
	SIDE	176,840	-1.7317	1.0000
	REAR	270,610	-1.8330	0.9990
BUFFERED STORAGE/ MODULAR IGLOO	FRONT*	278.08	-1.5458	0.9874
	SIDE*	180.46	-1.3917	0.9885

NOTE: Fit is of the form : P=A*Range^B

* Scaled to 1 pound

TABLE 4-3. MAGAZINE AIRBLAST DATA COMPARED TO STANDARD

NOTE: Shown are distances (in feet) to each specified pressure level

EVENT	DIRECTION	PRESSURE LEVEL (psi)												
		11.7	8	3.5	3	2.3	2.2	1.7	1.4	1.3	1.2	0.9	0.725	0.29
NOTS 6	FRONT	372	477	821	908	1080	1112	13.7	1496	1570	1655	1998	2301	4195
	SIDE	241	330	653	742	923	958	1185	1391	1479	1580	2003	2393	(5098)
	REAR	269	34[illegible]	578	638	755	776	914	1033	1083	1139	1367	1567	(2800)
	STANDARD	**433**	**52[illegible]**	**865**	**961**	**1154**	**1201**	**1442**	**1682**	**1802**	**1923**	**2403**	**2821**	**5527**
ESKIMO I	FRONT	405	524	918	1019	1220	1258	1498	1709	1797	1897	2306	2670	(4972)
	SIDE	320	440	884	1007	1260	1308	1626	1915	2039	2181	2780	3336	(7227)
	REAR	313	415	766	859	1046	1081	1310	1513	1598	1696	2100	2465	(4869)
	STANDARD	**526**	**643**	**1053**	**1170**	**1404**	**1462**	**1754**	**2047**	**2193**	**2339**	**2924**	**3433**	**6725**
ESKIMO III	FRONT	621	765	1202	1308	1512	1550	1784	1984	2066	2159	2527	2844	(4695)
	SIDE	564	723	1238	1369	1627	1675	1982	2249	2360	2486	2998	3451	(6268)
	REAR	430	554	959	1062	1267	1305	1549	1762	1851	1952	2362	2726	(5010)
	STANDARD	**649**	**793**	**1297**	**1441**	**1730**	**1802**	**2162**	**2522**	**2703**	**2883**	**3604**	**4231**	**8289**
ESKIMO VI	FRONT	352	421	618	664	752	768	866	948	981	1018	1165	1288	(1975)
	SIDE	259	323	520	569	663	680	789	883	922	965	1140	1291	(2192)
	REAR	240	296	464	505	584	598	689	765	797	833	974	1096	(1807)
	STANDARD	**334**	**409**	**669**	**743**	**892**	**929**	**1115**	**1300**	**1393**	**1486**	**1858**	**2181**	**4273**
BUFFERED STORAGE/ MODULAR IGLOO	FRONT*	7.8	9.9	17.0	18.7	22.2	22.9	27.0	30.7	32.2	33.9	40.8	46.9	84.9
	SIDE*	7.1	9.4	17.0	19.0	23.0	23.7	28.6	32.8	34.6	36.7	45.1	52.7	101.8
	REAR*				NO DATA									
	STANDARD	**9.0**	**11.0**	**18.0**	**20.0**	**24.0**	**25.0**	**30.0**	**35.0**	**37.5**	**40.0**	**50.0**	**58.7**	**115.0**

NOTES:
(1) Numbers in ( ) are extrapolations
(2) Shaded numbers are those that exceed the standard
(3) Scaled to 1 pound
(4) Distances shown are computed using least squares fits given in Table 4-2

CHAPTER 5

DISCUSSION OF AIRBLAST RESULTS

It would be extremely useful if the airblast data presented in the previous chapter could be collapsed into a set of curves representing the three directions (front, side, and rear) for all types of igloos. A basic approach would be to use cube-root or Hopkinson-Cranz scaling. A basic assumption here, however, is that the amount of earth cover and the type of construction are of secondary importance to the phenomena being considered (pressure and debris throw).

The information presented in the last chapter (both the igloo data and the buffered storage/modular igloo) has been scaled by the cube root of the equivalent TNT charge weight. The results are presented in Figures 5-1 to 5-6 for the igloo/Eskimo data. When the buffered storage/modular igloo data are included, the results are shown in Figures 5-7 and 5-8. Bad or erroneous data points have been eliminated. Both sets of data (Eskimo and Buffered Storage/Modular Igloo) appear to be from the same family. Least squares curves have been fit to each set of data, separately, as well as to the combined data. Shown on the figures are the results of a power law fit of the form:

$$F = A*\lambda B$$

where:

F	=	either peak pressure (P) in psi or scaled positive impulse ($I/W^{1/3}$) in psi-ms/$lb^{1/3}$
λ	=	scaled distance ($R/W^{1/3}$) in ft/$lb^{1/3}$
R	=	distance (feet)
W	=	equivalent TNT charge weight (pounds)
A,B,C	=	fitting coefficients.

A power law fit represents a straight line to the logarithms of the data. In addition to this fit, a second order polynomial was also fit to the logarithms of the pressure-distance data. The form of this fit is shown below:

$$F = A*\lambda(B + C * \ln(\lambda))$$

The improvement in the correlation coefficient was, at best, marginal. Table 5-1 presents a summary of all of the curve fitting coefficients.

EQUIVALENT WEIGHT

The definition of equivalent weight is the weight of a standard explosive required to produce a selected shock wave parameter of equal magnitude to that produced by a unit weight of the explosive in question. The standard which is used is

the Kingery hemispherical TNT standard.[19] The selected shock wave parameters are peak pressure and positive impulse.

Using the second order polynomial curve fit to the logarithms of the pressure-distance data and a power law fit to the impulse-distance data (Table 5-1), Figures 5-9 to 5-11 were generated. These are the equivalent weight versus pressure curves for the three directions. The curves for the pressure and impulse outside a detonating earth-covered magazine are not parallel to the Kingery standard. Because of this, the equivalent weight varies with the range (pressure level). It is still useful, however, to talk about an average equivalent weight. These are presented in Table 5-2.

GENERALIZED PREDICTIONS FOR PEAK PRESSURE

The least squares curve fits presented in Table 5-1 can be used to make generalized predictions. However, because of the nature of the data and because the data are coming from such varied sources, the upper bound of the 90 percent confidence interval for a power law fit will be used. The equations of these upper bound curves are presented in Table 5-3. Figure 5-12 compares the 90 percent upper bound composite of the Eskimo pressure-distance data with the Kingery hemispherical standard. Figure 5-13 presents similar comparisons for positive impulse. Figure 5-14 presents comparisons based on a composite of the igloo and buffered storage/modular igloo data.

To be safety conservative, the upper bound of the 90 percent confidence interval should not exceed the values prescribed in the DOD standards and guidelines. This comparison is presented in Table 5-4. As can be seen, only one of the values exceed the standard–out the side at the 0.9 psi level for the Eskimo data. Because of the limited amount of data out the side and rear, definitive conclusions cannot be reached. However, it appears that the standard is not met in the side direction at the lower pressure levels.

The limited amount of airblast data recorded on the HASTINGS IGLOO tests indicate pressures occurring at much shorter ranges than those given by the standards–scaled distances between 11 and 31 $ft/lb^{1/3}$, while the standard would indicate distances on the order of 40 or greater for the measured pressure levels (1.2 psi).

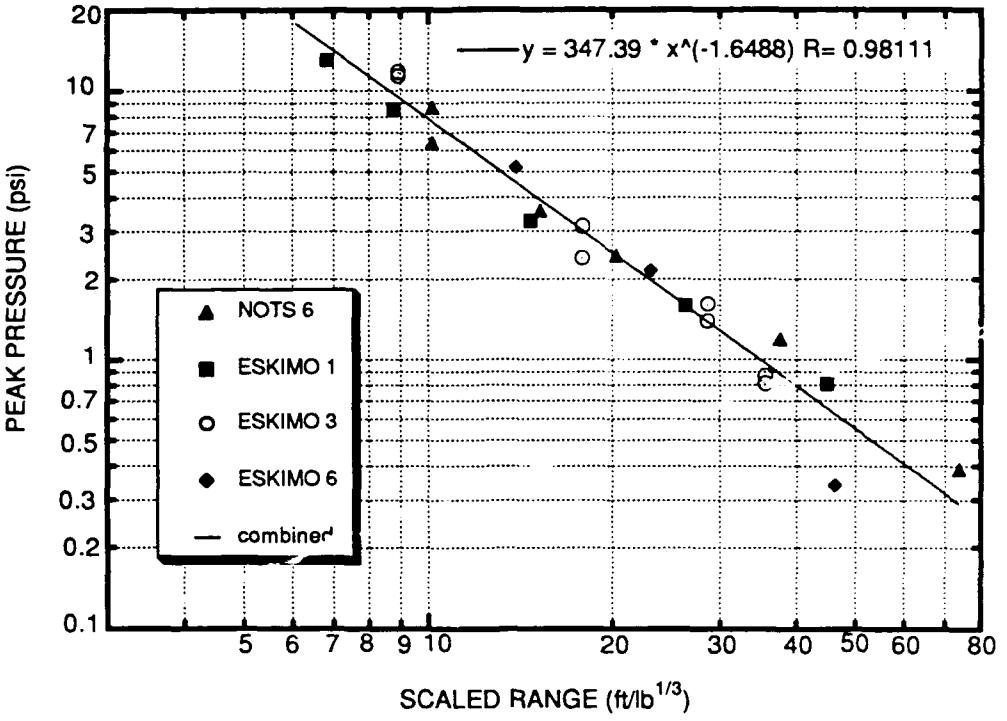

FIGURE 5-1. SCALED PRESSURE-DISTANCE OUT FRONT OF IGLOO

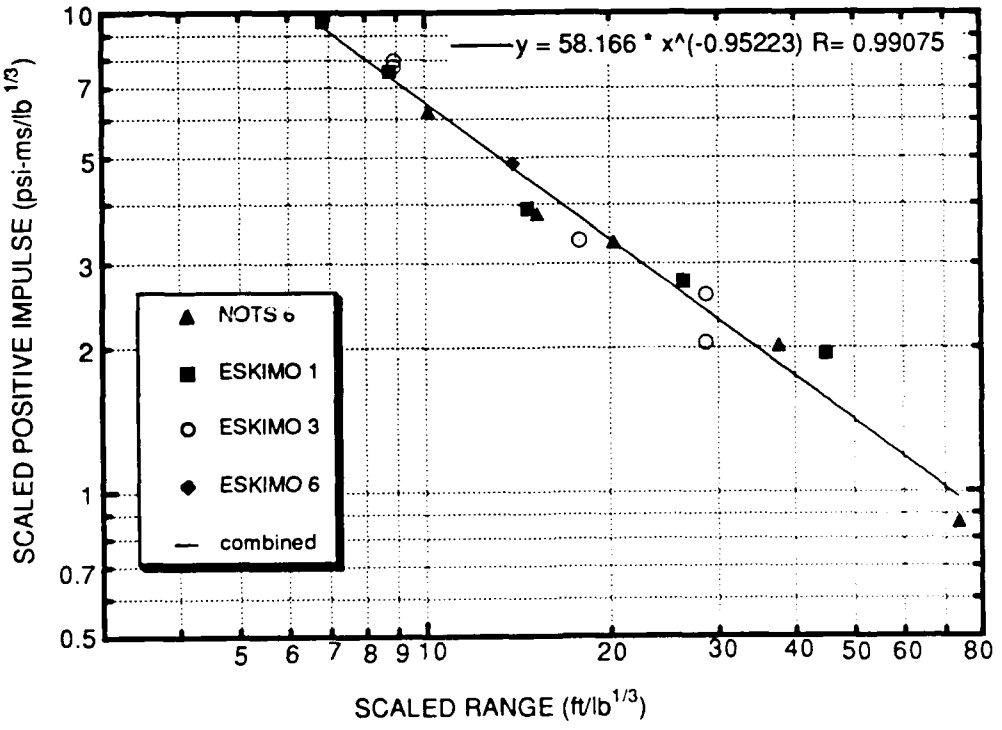

FIGURE 5-2. SCALED IMPULSE-DISTANCE OUT FRONT OF IGLOO

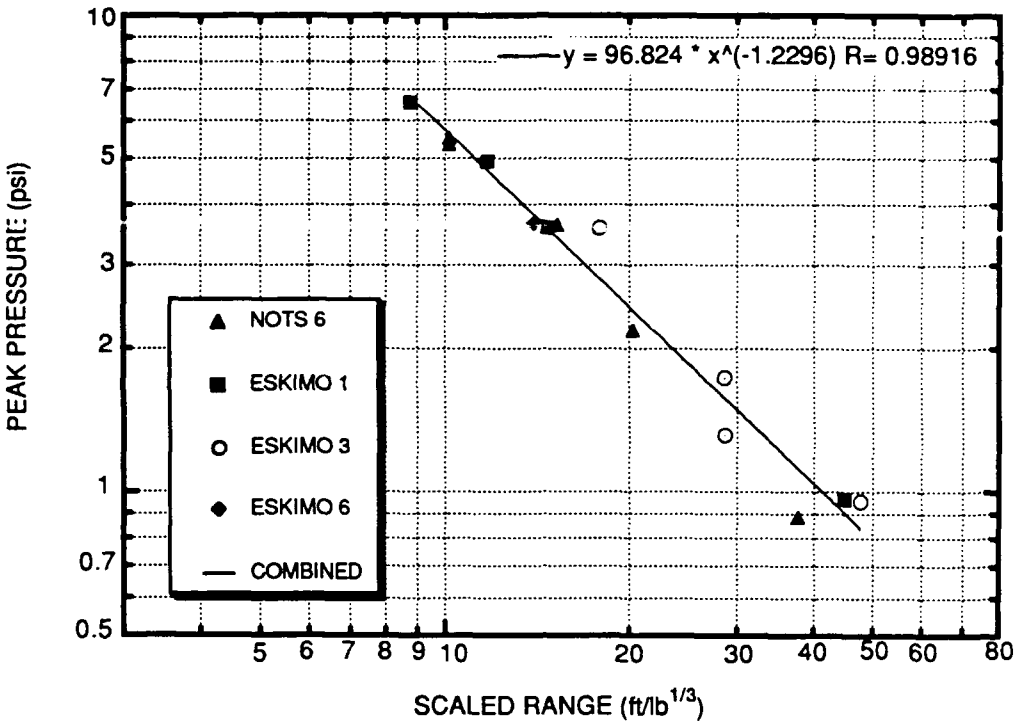

FIGURE 5-3. SCALED PRESSURE-DISTANCE OFF SIDE OF IGLOO

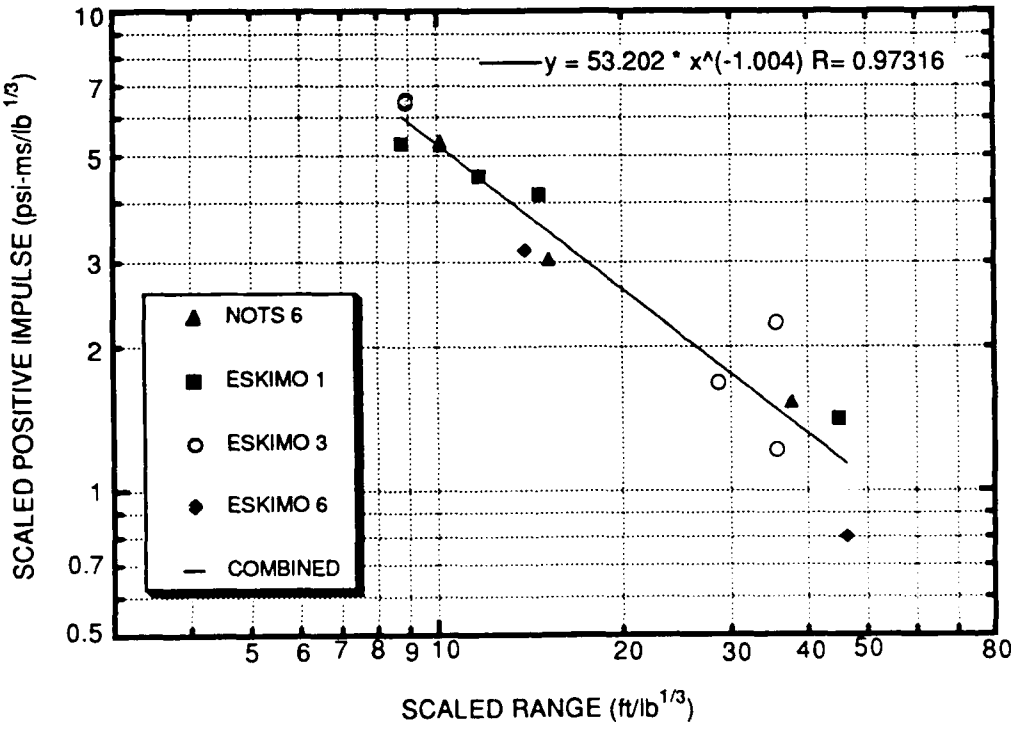

FIGURE 5-4. SCALED POSITIVE IMPULSE OFF SIDE OF IGLOO

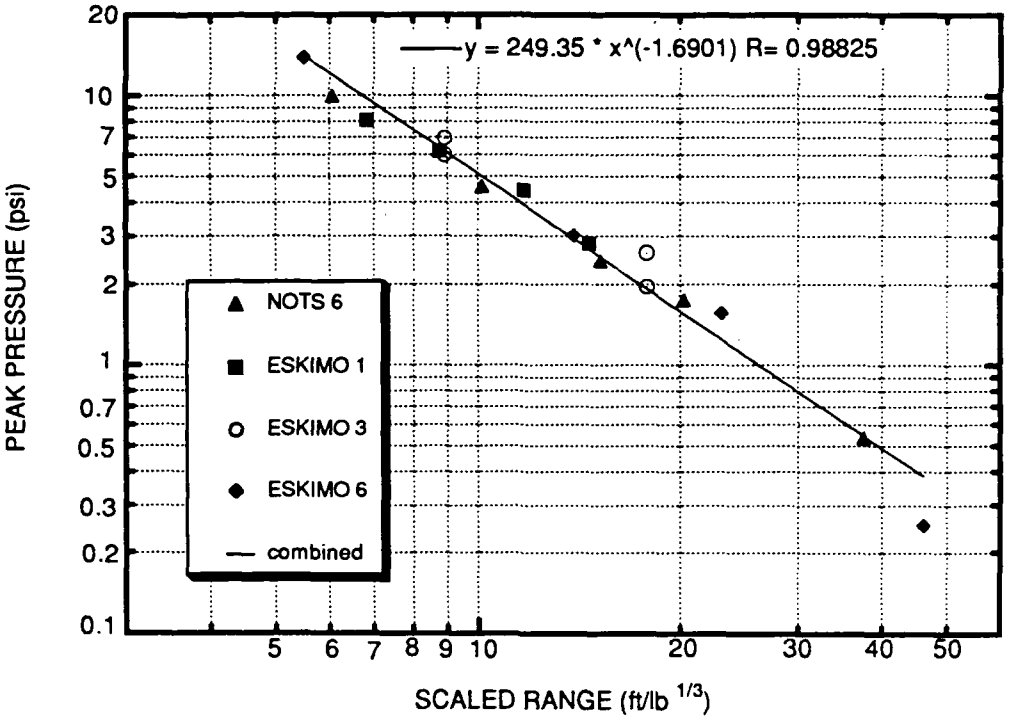

FIGURE 5-5. SCALED PRESSURE-DISTANCE OUT REAR OF IGLOO

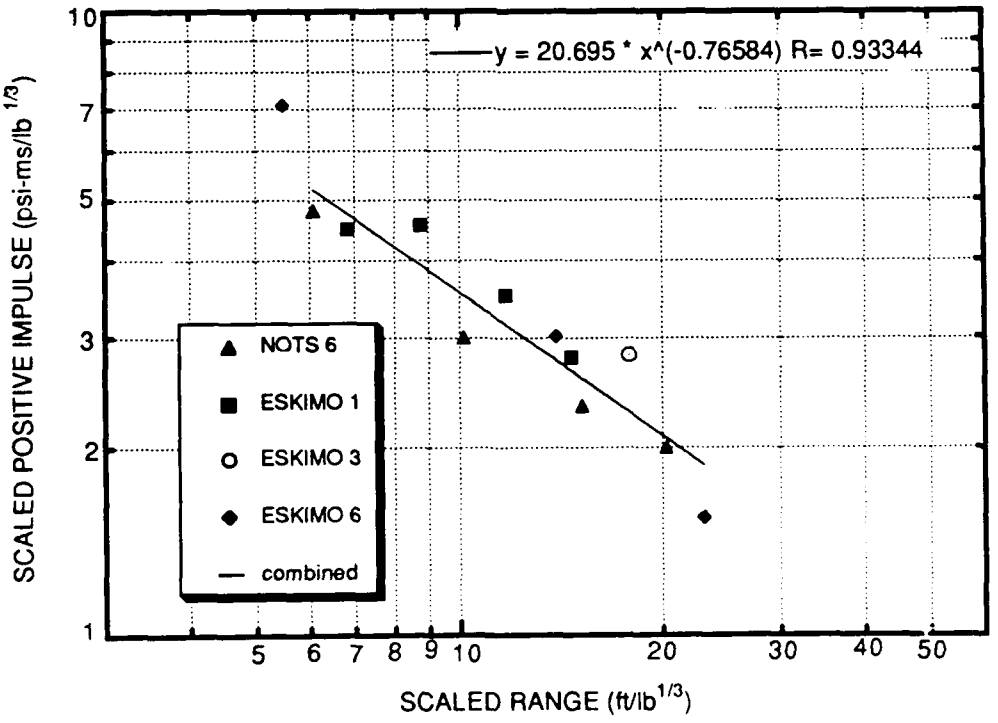

FIGURE 5-6. SCALED IMPULSE-DISTANCE OUT REAR OF IGLOO

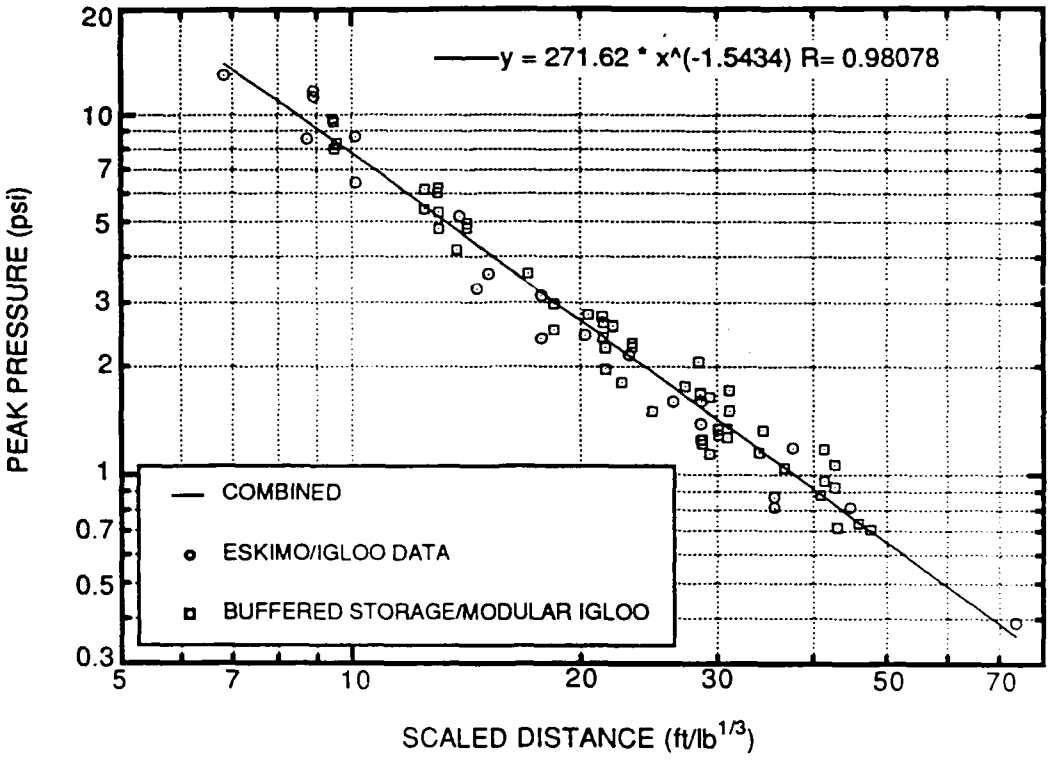

FIGURE 5-7. SCALED PRESSURE-DISTANCE DATA (FRONT)

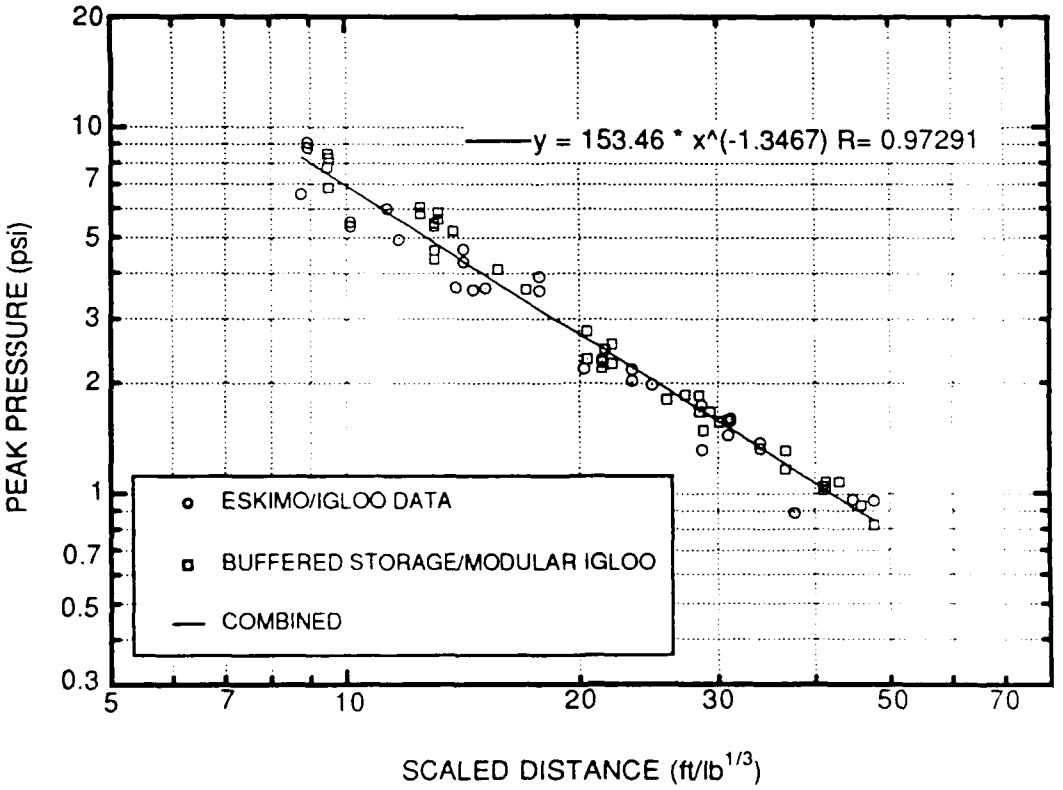

FIGURE 5-8. SCALED PRESSURE-DISTANCE DATA (SIDE)

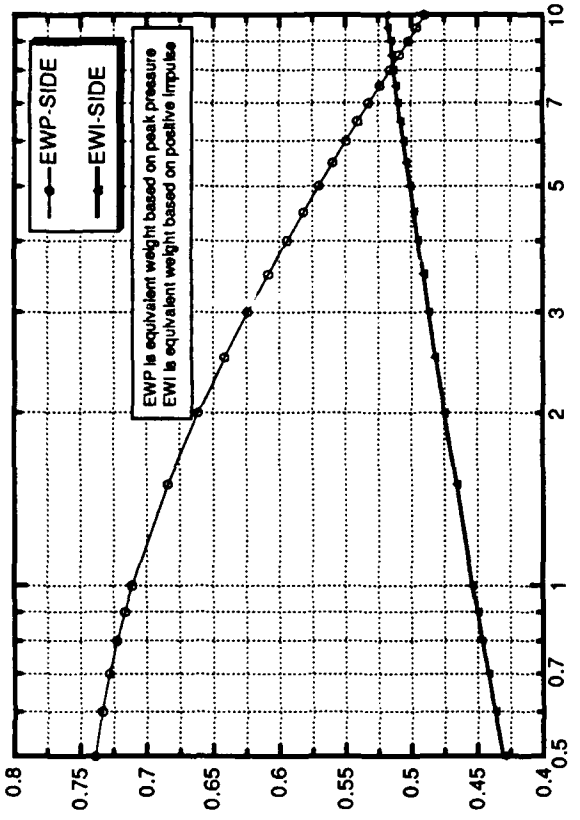

FIGURE 5-10. IGLOO EQUIVALENT WEIGHT (SIDE)

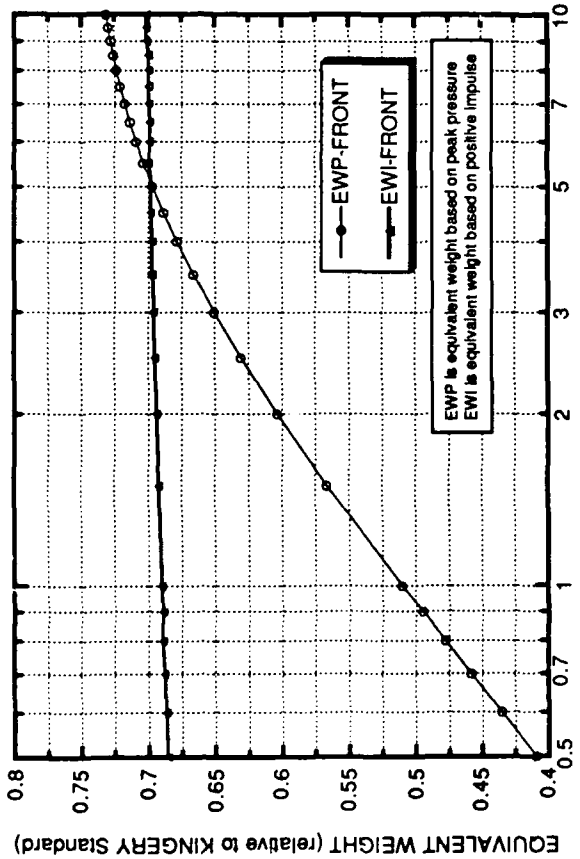

FIGURE 5-9. IGLOO EQUIVALENT WEIGHT (FRONT)

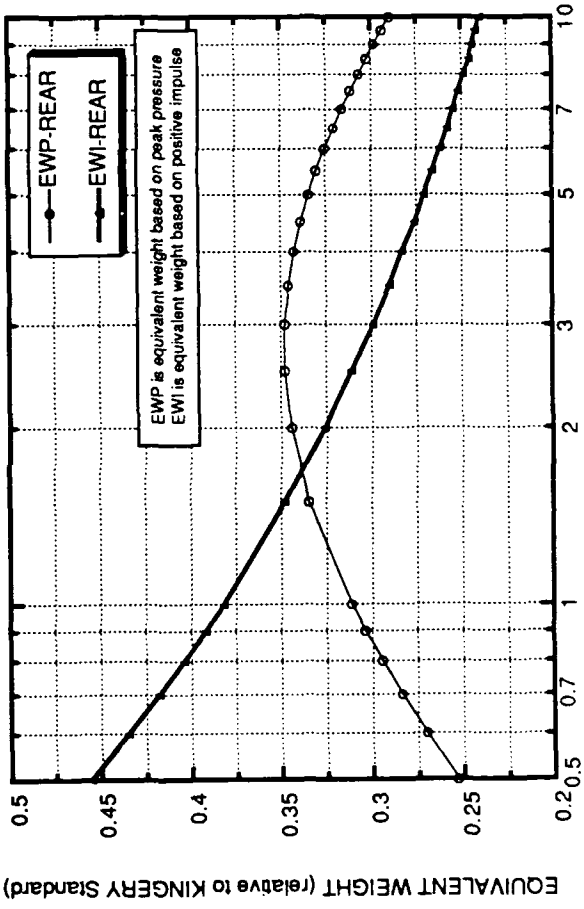

FIGURE 5-11. IGLOO EQUIVALENT WEIGHT (REAR)

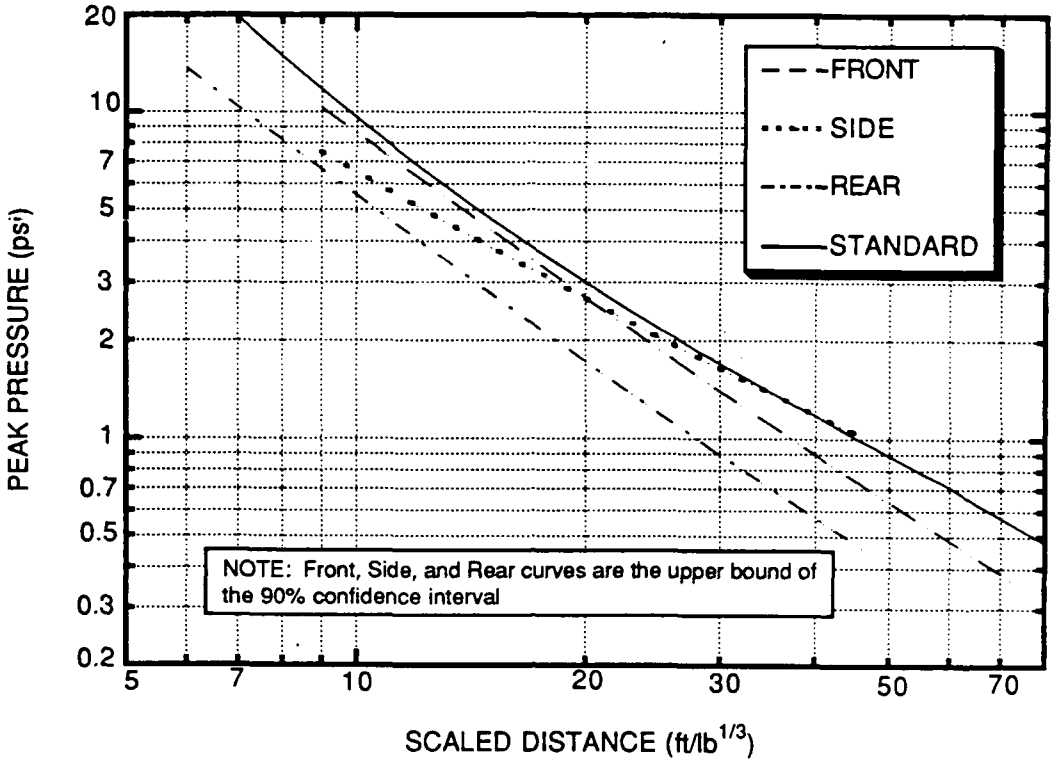

FIGURE 5-12. COMPARISON OF UPPER BOUND ESKIMO PRESSURE-DISTANCE CURVES WITH HEMISPHERICAL STANDARD

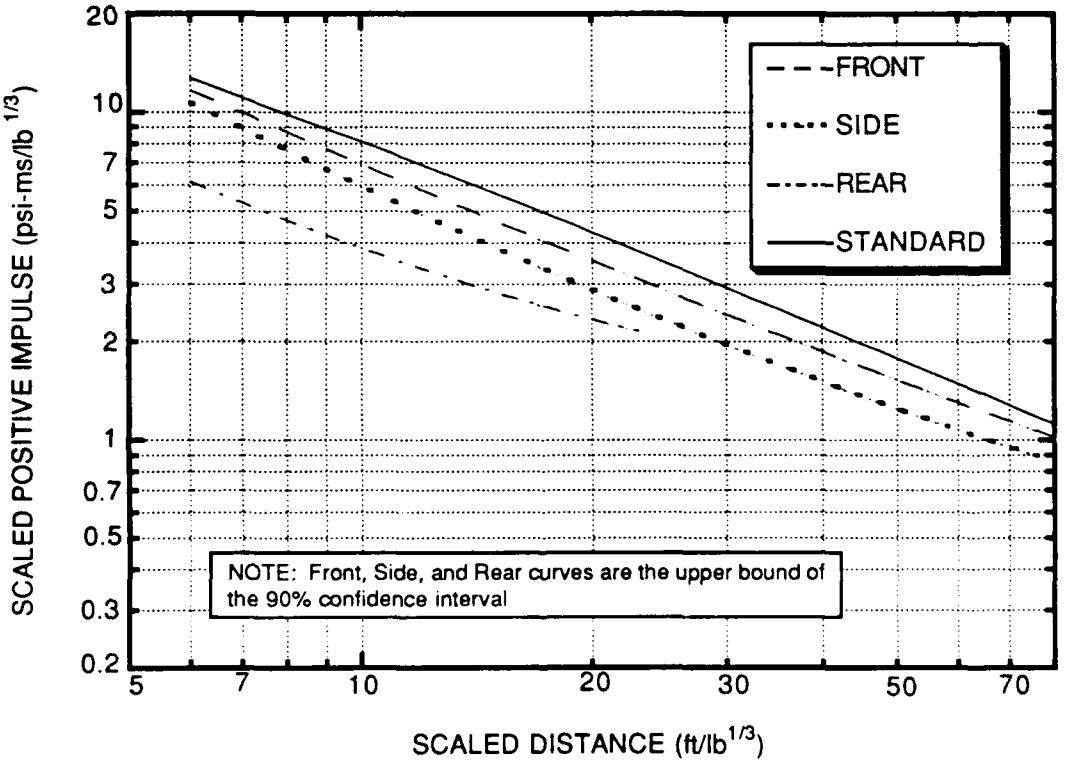

FIGURE 5-13. COMPARISON OF UPPER BOUND ESKIMO IMPULSE-DISTANCE CURVES WITH HEMISPHERICAL STANDARD

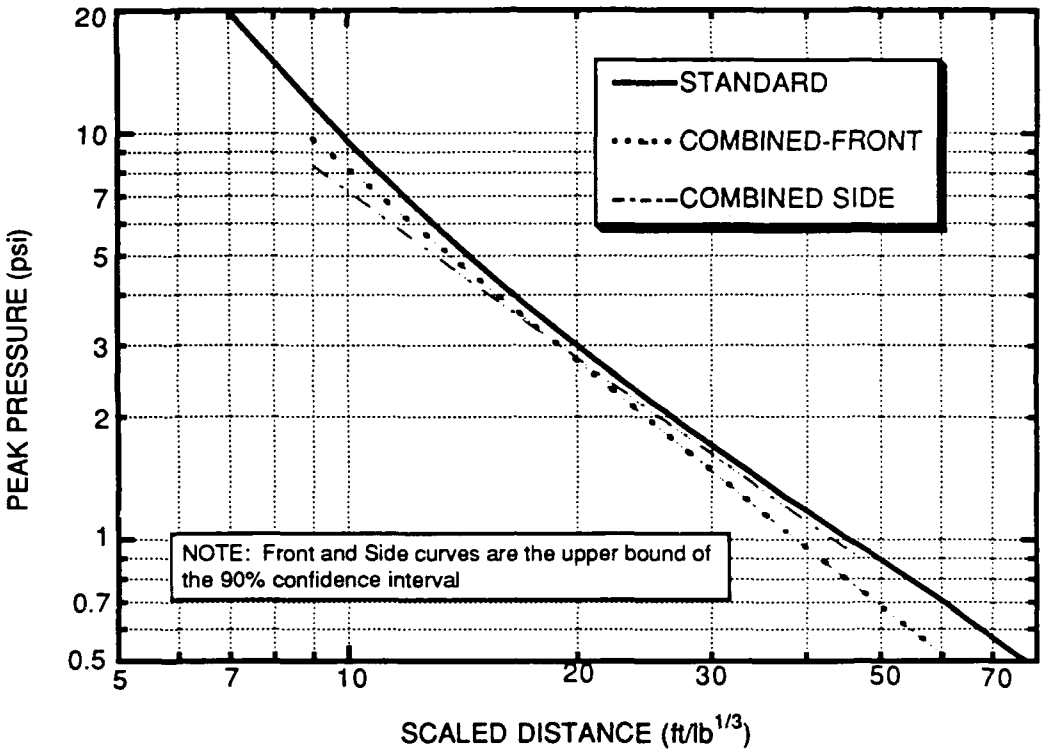

FIGURE 5-14. COMPARISON OF UPPER BOUND COMPOSITE PRESSURE-DISTANCE CURVES WITH HEMISPHERICAL STANDARD

TABLE 5-1. LEAST SQUARES CURVE FIT COEFFICIENTS

EVENT	DIRECTION	PRESSURE			
		A	B	C	Correlation Coefficient
ESKIMO	FRONT	347.39	-1.6488		0.9811
		839.44	-2.3355	0.1283	0.9887
	SIDE	96.824	-1.2296		0.9892
		223.91	-1.7021	0.0668	0.9780
	REAR	249.35	-1.6901		0.9883
		246.40	-1.8865	0.0845	0.9899
COMBINED: ESKIMO/ BUFFERED STORAGE/ MODULAR IGLOO	FRONT	271.62	-1.5434		0.9808
		674.16	-2.1628	0.1025	0.9841
	SIDE	153.46	-1.3467		0.9729
		213.27	-1.5718	0.0374	0.9866
	REAR	249.35	-1.6901		0.9883
		246.40	-1.8865	0.0845	0.9899
		IMPULSE			
ESKIMO	FRONT	58.166	-0.9522		0.9908
	SIDE	53.202	-1.0040		0.9732
	REAR	20.695	-0.7658		0.9334

NOTES:

(1) Fit is of the form: F=A*Z^(B+C*ln(Z))

(2) Z is scaled distance (ft/lb^1/3)

(3) The impulse data for buffered storage/modular igloo were not used

TABLE 5-2. IGLOO EQUIVALENT WEIGHTS

DIRECTION	EW-P	EW-I	OVERALL
FRONT	0.63	0.70	0.66
SIDE	0.61	0.49	0.55
REAR	0.32	0.31	0.31

EW-P is equivalent weight based on peak pressure
EW-I is equivalent weight based on positive impulse

NOTE: Standard is Kingery hemispherical TNT standard

TABLE 5-3. UPPER BOUND 90 PERCENT CONFIDENCE INTERVAL

PRESSURE

EVENT	DIRECTION	A	B	C	VALIDITY RANGE*
IGLOO	FRONT	628.571	-2.010953	0.063505	8.8-73.6
	SIDE	224.076	-1.730805	0.084232	8.8-44.8
	REAR	431.713	-2.050523	0.068671	5.5-46.1
COMBINED IGLOO/ BUFFERED STORAGE/ MODULAR IGLOO	FRONT	386.34	-1.751924	0.033707	8.8-73.6
	SIDE	209.305	-1.536008	0.031268	8.8-44.8
	REAR		SEE ABOVE		5.5-46.1

IMPULSE

EVENT	DIRECTION	A	B	C	VALIDITY RANGE*
IGLOO	FRONT	83.579	-1.16503	0.03633	8.8-73.6
	SIDE	116.909	-1.48347	0.08258	8.8-44.8
	REAR	59.984	-1.55014	0.15607	5.5-22

*Scaled distance (ft/lb^1/3)

Fit is of the form: F=A*Z^(B+C*ln(Z))

Z is scaled distance in ft/lb^1/3

F is either peak pressure in psi or scaled positive impulse in psi-ms/lb^1/3

TABLE 5-4. COMPARISON OF STANDARD WITH UPPER BOUND OF PREDICTIONS

NOTE: Shown are scaled distances (ft/lb^1/3) to each specified pressure level

		PRESSURE LEVEL												
		11.7 psi	8.0 psi	3.5 psi	3.0 psi	2.3 psi	2.2 psi	1.7 psi	1.4 psi	1.3 psi	1.2 psi	0.9 psi	0.725 psi	0.29 psi
ESKIMO	FRONT	8.4*	10.4	17.0	18.7	22.0	22.6	26.6	30.0	31.5	33.1	39.9	45.9*	85.0*
	SIDE	6.5*	8.6	16.1	18.2	22.6	23.5	29.2	34.6	36.9	39.7	51.5*	BEYOND RANGE OF DATA	
	REAR	6.5	8.1	13.4	14.3	16.8	17.2	20.1	22.7	23.7	24.9	29.9	34.3	62.5*
	STANDARD	9.0	11.0	18.0	20.0	24.0	25.0	30.0	35.0	37.5	40.0	50.0	58.7	115.0

		PRESSURE LEVEL												
		11.7 psi	8.0 psi	3.5 psi	3.0 psi	2.3 psi	2.2 psi	1.7 psi	1.4 psi	1.3 psi	1.2 psi	0.9 psi	0.725 psi	0.29 psi
COMPOSITE	FRONT	8.0*	10.1	17.1	18.9	22.4	23.1	27.3	31.0	32.6	34.4	41.7	48.0*	89.7*
	SIDE	7.1*	9.3	16.9	18.9	23.0	23.8	28.9	33.4	35.4	37.6	46.8*	BEYOND RANGE OF DATA	
	REAR													
	STANDARD	9.0	11.0	18.0	20.0	24.0	25.0	30.0	35.0	37.5	40.0	50.0	58.7	115.0

*extrapolated value

NOTE: all distances shown are scaled distances (ft/lb^1/3)

areas marked in this fashion are regions where the standard is exceeded

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APPENDIX A

FRAGMENTATION/DEBRIS DATA

NOTS TEST 5

Donor: Three complete missiles–total weight of energetic material = 1,275 pounds

Date: 4 April 1963

FRAGMENT DISTRIBUTION, TEST NO. 5

Fragment ID No.	Description
1	Large piece corrugated steel arch, #1.
2	Four large pieces corrugated steel arch (in immediate vicinity of crater and near acceptor igloo C), #2.
3	Concrete fragment with reinforcing rods (11" x 14" x 17"), #3.
4	Bottom right side of donor door frame and pilaster, #4.
5	Motor entrance nozzle, #5.
6	Top piece of south door of donor (45" x 42"), #6.
7	Bottom piece of south door of donor (51" x 56"), #7.
8	Piece of north door of donor (44" x 38"), #8.
9	Piece of corrugated steel arch (45" x 38").
10	Small (about 5 lb) concrete fragment (6" x 7" x 8").
11	Large concrete fragment with reinforcing rods (40" x 29" x 17").
12	Large concrete fragment with reinforcing rods (39" x 26" x 16").
13	Motor exit nozzle.
14	Piece of motor (about 8 lb).
15	Piece of motor (about 10 lb).
16	Piece of motor (about 5 lb).
17	Limitation of debris.
18	Large piece of concrete with reinforcing rods. Part of donor door frame and pilaster (est. 6' x 20" x 18").
19	Piece of door frame.
20	Motor entrance and exit nozzles (attached).
21	Motor exit nozzle.
22	Large piece metal door frame.
23	Concrete fragment (about 50 lb).
24	Piece of donor door (24" x 24").
25	Plow-shaped piece of donor metal door frame.
26	Piece of metal donor door frame.
27	Part of donor door hinge-strap.
28	Small part of internal door framing.

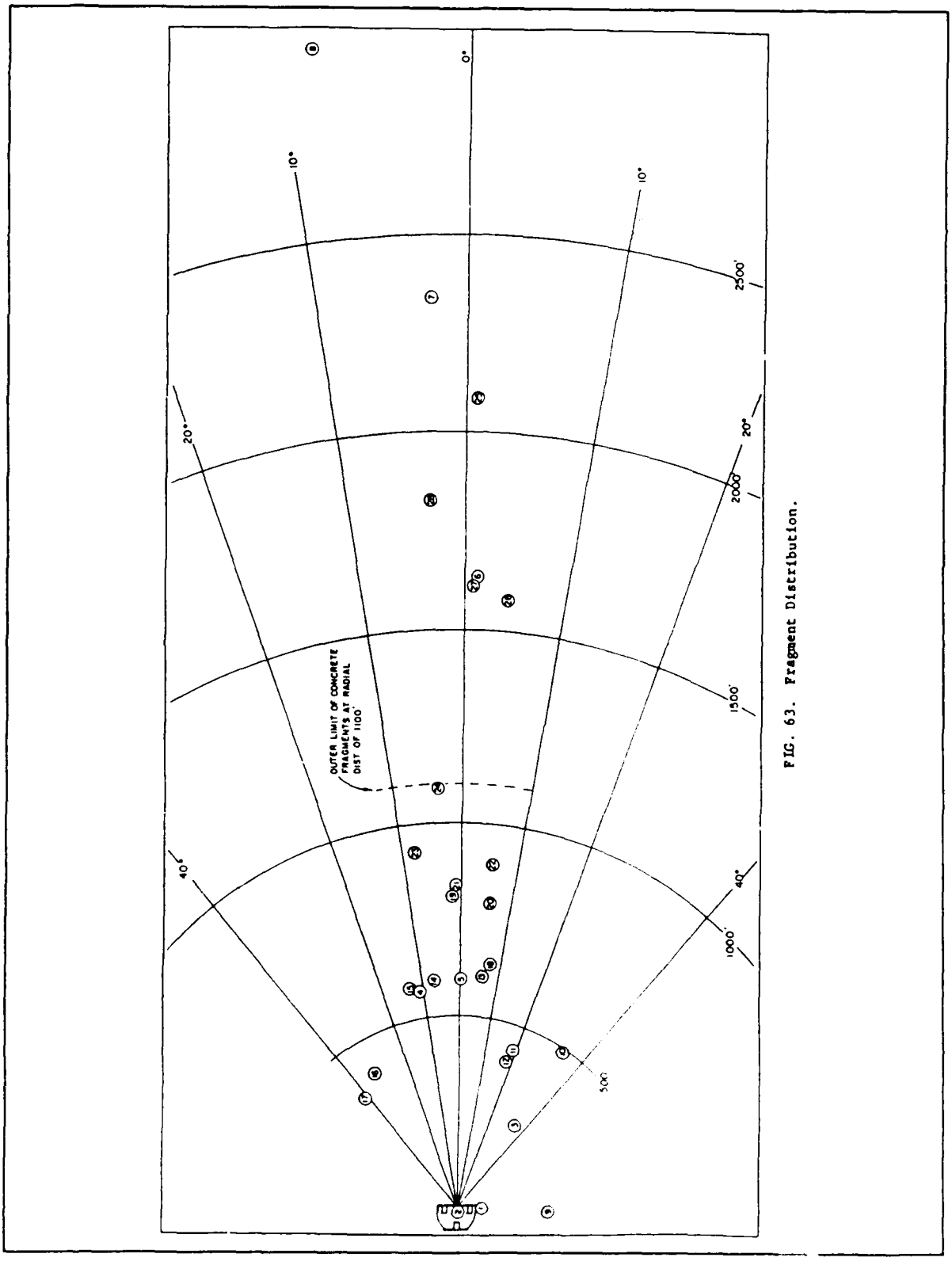

FIG. 63. Fragment Distribution.

ESKIMO 1 DEBRIS

Range (ft)	Type of Pickup	Hazardous Fragment/Debris Density (number/10000 ft^2)				
		Front	Side	Rear	F/S Diagonal*	R/S Diagonal*
601.5	Magnetic		695.5			
625.0	Magnetic	425.3		231.8		
851.5	Magnetic		299.7			
875.0	Magnetic	241.7		155.4		
1000.0	Hand			296.0		
1025.0	Hand	364.9	335.6			
1125.0	Magnetic	199.4	262.6	105.7		
1375.0	Magnetic	210.5	208.4	101.4		
1525.0	Hand		154.8			
1559l.0	Magnetic	180.9		1750.0		
1750.0	Magnetic		100.8			
1850.0	Hand					18.9
1950.0	Hand					6.7
2018.0	Hand	303.8				
2050.0	Hand		63.3	41.8		14.3
2150.0	Hand					3.0
2250.0	Magnetic		14.1			
2250.0	Hand		54.0	13.9		3.1
2350.0	Hand				32.5	
2450.0	Hand		36.3	7.8		
2650.0	Hand				19.8	
2740.0	Hand		7.7			
2750.0	Hand				14.5	
2850.0	Hand	44.3			10.7	
2950.0	Hand		2.9		10.4	
3050.0	Hand	26.8			3.5	
3150.0	Hand	19.9				
3250.0	Hand	13.5				
3350.0	Hand	18.6				
3450.0	Hand	11.7				

CHARGE WEIGHT: 200,000 pounds TNT

STRUCTURE WEIGHT: 5,000 pounds
COVER WEIGHT: 4,890,000 pounds

DATE: 8 December 1971
Barometric Pressure: 936.0 mbar (13.58 psi)
Temperature: 55°F

GAUGE TYPE: BRL Self-Recording
DONOR: 13,696 155-mm TNT-loaded projectiles

REFERENCE: NWC TP 5430

*F/S is diagonal between front and side R/S is diagonal between rear and side

NOTE: DDESB Criterion of 1 hazardous fragment/600 ft^2 corresponds to 16.67 fragments/10000ft^2

Appendix E

ESKIMO VI DEBRIS STUDY

Figure E-1 summarizes the results of a debris study conducted following the ESKIMO VI test. The objective of the study was to quantify the amount and size of fragments generated by the test. These data will be used to estimate initial velocities of the particles and will be entered into the NCEL data base for explosion-generated fragmentation. Only large items were listed (tabulated in Table E-1) out to a range of about 2,000 feet. Special attention was paid to the wingwall trajectories (items 21 and 22) since they were the largest projectiles generated by the test. In general, most fragments were generated by the roof breakup.

Figure E-2 illustrates the soil distribution following the test.

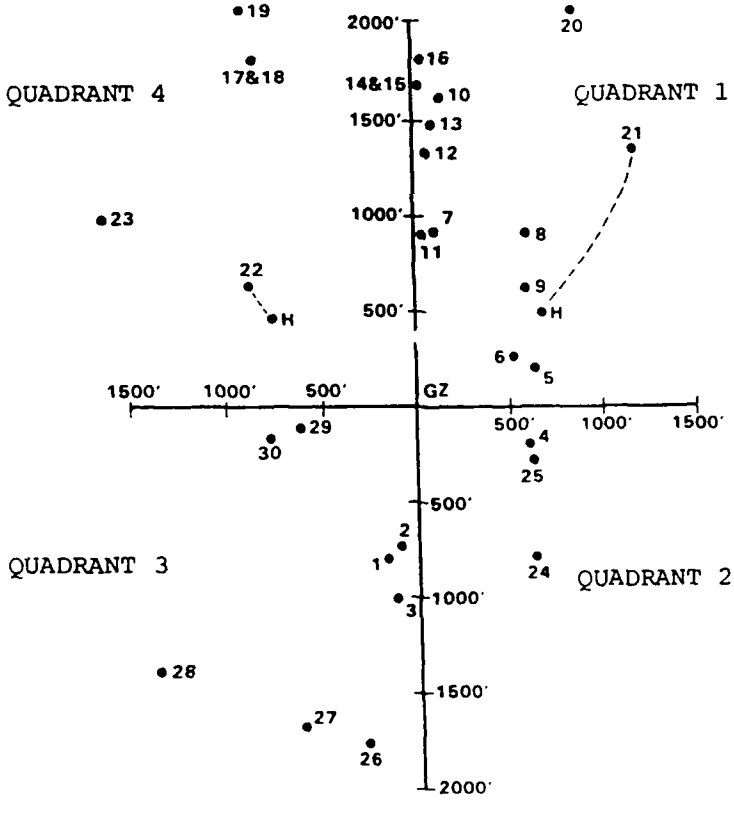

Figure E-1. ESKIMO VI debris collection.

Table E-1. ESKIMO VI Debris Collection

Item No.	Distance From Ground Zero (ft)	Quadrant	Weight (lb)	Description
1	810	3	80	7-ft 6-in. I-beam
2	760	3	122	6 x 2-ft plate
3	1,010	3	102	5 x 2-ft plate
4	493	2	245	4 x 6-ft plate
5	635	1	46	1-1/2 x 3-ft plate
6	583	1	184	3 x 6-ft plate
7	920	1	204	4 x 5-ft plate
8	1,218	1	56	7-ft channel
9	850	1	81	4 x 2-ft plate
10	1,622	1	81	2 x 4-ft plate
11	900	1	326	4 x 8-ft plate
12	1,345	1	242	3 x 8-ft plate
13	1,499	1	60	4-ft 6-in. channel
14	1,690	1	20	2-ft 4-in. channel
15	1,690	1	81	2 x 4-ft plate
16	1,768	1	92	12-ft 4-in. I-beam
17	2,036	4	39	5-ft 4-in. I-beam
18	2,036	4	54	7-ft 4-in. I-beam
19	2,367	4	85	5-ft 8-in. I-beam
20	2,224	1	85	5-ft 8-in. I-beam
21	1,641	1	1,913	47-ft^2 1-in. plate
21-H	837	1	--	First impact of #21
22	1,082	4	1,913	47-ft^2 1-in. plate
22-H	897	4	--	First impact of #22
23	1,912	4	122	3 x 4-ft plate
24	1,003	2	142	2 x 7-ft plate
25	686	2	245	4 x 6-ft plate
26	1,811	3	270	5-ft 10-in. I-beam
27	1,791	3	54	7-ft 4-in. I-beam
28	1,952	3	82	4 x 2-ft plate
29	639	3	300	12 x 3-ft plate
30	825	3	180	6 x 3-ft plate

Figure E-2. Aerial view of the ESKIMO VI site's final soil distribution.

HASTINGS IGLOO--60 POUND TEST

DISTANCE (FT)	HAZARDOUS FRAGMENT DENSITY(number /600 ft^2)		
	0-5°	5-10°	10-45°
100	6.3	4.7	9
125	24.3	21.9	26.8
150	19.9	10	7.1
175	40.4	25	23.2
200	19.4	12.7	6.3
225	18	9.7	4.7
250	20.7	13.3	3.1
275	10.4	6.3	1.8
300	2	1.5	0.3
325	1.8	2.2	1.1
350	1.6	0.8	0.6
375	1.5	0.8	0.2
400	0	0	0.8
425	1.4	0.7	0.1
450			
475			
500			
525			
550			
575			
600			
625			
650			
675			
700			
725			

HASTINGS IGLOO--80 POUND TEST

DISTANCE (FT)	HAZARDOUS FRAGMENT DENSITY(number /600 ft^2)		
	0-5°	5-10°	10-45°
100	0	0	2.8
125	0	0.6	2.1
150	10	10.5	3.8
175	28.6	16.8	4.6
200	20.4	13.2	4.2
225	15.5	10.7	7
250	18.4	10.9	2.9
275	4.1	3.1	1.2
300	11.4	6.6	2.4
325	0.9	1.3	1.9
350	2.4	1.6	3.2
375	3	1.5	0.8
400	5.6	3.2	1.5
425	0.7	0.7	0.1
450	1.3	0.8	0.3
475	1.2	0.6	0.2
500	2.8	1.7	0.7
525	1.1	0.5	0.1
550			
575			
600			
625			
650			
675			
700			
725			

HASTINGS IGLOO--100 POUND TEST

DISTANCE (FT)	HAZARDOUS FRAGMENT DENSITY(number /600 ft^2)		
	0-5°	5-10°	10-45°
100	0	0	3.5
125	0	2.4	3.1
150	23.8	18.8	9.3
175	16.8	15.8	8.5
200	3	8	6.9
225	0	5.8	1.4
250	20.8	15	4.1
275	2	4.1	2.1
300	3.8	3.6	1.1
325	3.6	3.1	0.9
350		0.4	0.7
375		1.1	2.5
400		0.7	0.6
425		0.7	1.2
450			
475			
500			
525			
550			
575			
600			
625			
650			
675			
700			
725			

HASTINGS IGLOO--150 POUND TEST

DISTANCE (FT)	HAZARDOUS FRAGMENT DENSITY(number /600 ft^2)		
	0-5°	5-10°	10-45°
100	3.1	2.4	3.8
125	0	3	6.1
150	21.9	12.5	9.5
175	10.2	5.9	3.2
200	19.1	12.5	6.4
225	3.9	3.8	2.6
250	1.2	1.2	1.1
275	7.2	6.2	1.6
300	5.8	4.8	1.8
325	4.5	2.9	0.8
350	4.8	4.6	2.3
375	9.9	5.5	1.3
400	4.2	3	1
425	4.7	2.7	0.7
450	3.2	1.8	0.6
475	2.4	2	0.4
500	2.3	1.7	1.1
525	3.2	2	0.8
550	5	2.6	0.7
575	0	0.1	0.2
600	1	0.7	0.7
625	2.2	1.3	0.7
650	2.2	1.4	0.3
675	0.4	0.3	0.4
700	0.4	0.2	0.1
725			0.2

APPENDIX B

AIRBLAST DATA

ARCO TEST 1

RANGE (ft)	PRESSURE (psi)		
	FRONT	SIDE	REAR
275	28.1	28.1	
330	18.5	18.5	
385	14.8	18.5	
440	12	14.8	
500	9.7	9.7	8.2
500	8.2		
565	8.2	8.2	
565	9.7	7.9	8.2
640	8.2	8.2	
640	7.9	7.9	8.2
725	8.2	8.2	
725	6.4	6.4	5.6
820	5.6	8.2	
820	5.2	6.4	5.6
930		5.6	
930	5.2	5.2	5.6
1055			
1055	5.6	3.3	3.3
1190	2.3	3.3	3.3
1350	3.3	2.3	3.3
1530	2.3	3.3	2.3
1730	1.5	3.3	1.5
1960	1.5	1.5	0.94
2220	1.5	0.94	1.5
2515	0.94	0.94	0.94
2845	0.6	0.94	0.6
3220	0.6	0.6	0.6
3645	0.38	0.38	0.38

NOTE: not scaled to sea level conditions

CHARGE WEIGHT: 500,340 pounds TNT

CASE WEIGHT: 429,660 pounds
STRUCTURE WEIGHT: 341,250 pounds
COVER WEIGHT: 4,500,000 pounds

DATE: 1 October 1946
Barometric Pressure: 25" (12.28 psi)
Temperature: 62°F

GAUGE TYPE: paper & foil

DONOR: 930 MK36 1000-pound TNT-loaded bombs

REFERENCE: ASESB Technical Paper No. 5

ARCO TEST 2

RANGE (ft)	PRESSURE (psi)		
	FRONT	SIDE	REAR
275	34.3	22.8	
330	34.3	14.8	
385	18.5	12	
440	14.8	12	
500		12	8.2
500	8.2		
565	12	9.7	
565	13.8	8.2	8.2
640	14.8	7.9	
640	8.2	8.2	8.2
725	9.7	6.4	
725	5.6	8.2	5.6
820	7.9	6.4	
820	5.6	5.6	5.6
930	6.4	5.2	
930	5.6	5.6	5.6
1055			
1055	3.3	3.3	3.3
1190	3.3	5.6	2.3
1350	3.3	2.3	2.3
1530	0.94	2.3	2.3
1730	1.5	1.5	1.5
1960	0.6	2.3	0.94
2220	0.6	0.6	0.6
2515	0.6	0.38	0.6
2845	0.25	0.38	0.6
3220	0.38	0.38	0.38
3645	0.6	0.38	0.38

NOTE: not scaled to sea level conditions

CHARGE WEIGHT: 500,340 pounds TNT

CASE WEIGHT: 429,660 pounds
STRUCTURE WEIGHT: 341,250 pounds
COVER WEIGHT: 6,300,000 pounds

DATE: 8 October 1946
Barometric Pressure: 25.19" (12.37 psi)
Temperature: 45°F

GAUGE TYPE: paper & foil

DONOR: 930 MK36 1000-pound TNT-loaded bombs

REFERENCE: ASESB Technical Paper No. 5

NOTS TEST 1

RANGE (ft)	PRESSURE (psi)		
	FRONT	SIDE	REAR/rear quarter
50	34.87		
59			3.49
65		4.14	3.07
65			3.39
65		4.34	
130	13.01		
130		2.07	
280	3.64		
590	0.99		-
590			0.33
590			0.35
1180	0.44		
1180			0.15
1180			0.19

NOTE: not scaled to sea level conditions

RANGE (ft)	IMPULSE (psi-ms)		
	FRONT	SIDE	REAR/rear quarter
50	44.1		
59			32.9
65		49	37.4
65			133.3
65		60.4	
130	155.8		
130		24.7	
280	24.4		
590	23.1		-
590			-
590			9.1
1180	9.9		
1180			4.6
1180			4.2

NOTE: not scaled to sea level conditions

CHARGE WEIGHT: 2,424 pounds TNT equivalent

CASE WEIGHT: 1,816 pounds
STRUCTURE WEIGHT: 3,000 pounds
COVER WEIGHT: 478,000 pounds

DATE: 17 January 1962
Barometric Pressure: 941.9 mbar (13.66 psi)
Temperature: 48°F

GAUGE TYPE: BRL Self-Recording

DONOR: 8 AN-M-64A1 500-pound Comp B-loaded bombs

REFERENCE: NOTS TP 3843

NOTS TEST 2

RANGE (ft)	PRESSURE (psi)		
	FRONT	SIDE	REAR/rear quarter
59			5.32
130	10.08		
130	9.63		
130			2.56
290	4.14		
290			1.09
366	2.38		
590	1.09		
590			0.4
1180	0.35		
1180			0.25

NOTE: *not scaled to sea level conditions*

RANGE (ft)	IMPULSE (psi-ms)		
	FRONT	SIDE	REAR/rear quarter
59			49.08
130	122.8		
130	105.97		
130			28.19
290	50.07		
290			18.85
366	37.26		
590	10.87		
590			9.02
1180	10.73		
1180			4.96

NOTE: not scaled to sea level conditions

CHARGE WEIGHT: 2,611 pounds TNT equivalent

CASE WEIGHT: 918 pounds
STRUCTURE WEIGHT: 3,000 pounds
COVER WEIGHT: 478,000 pounds

DATE: 6 April 1962
Barometric Pressure: 948.7mbar (13.76 psi)
Temperature: 48°F

GAUGE TYPE: BRL Self-Recording

DONOR: 9 MK54-1 350-pound HBX-1 loaded depth bombs

REFERENCE: NOTS TP 3843

NOTS TEST 6

RANGE (ft)	PRESSURE (psi)		
	FRONT	SIDE	REAR/rear quarter
300	20.98		
300			10.2
300		7.74	
500	8.87		
500	6.57		
500			4.69
500		5.49	
500		5.65	
750	3.67		
750			2.48
750		3.73	
1000	2.5		
1000			1.79
1000		2.24	
1855	1.22		
1855			0.55
1855		0.91	
3630	0.4		

NOTE: not scaled to sea level conditions

RANGE (ft)	IMPULSE (psi-ms)		
	FRONT	SIDE	REAR/rear quarter
300	-		
300			219.7
300		-	
500	284.14		
500	188.81		
500			136.98
500		239.96	
500		243.99	
750	173.28		
750			106.31
750		138.94	
1000	151.82		
1000			91.3
1000		-	
1855	92.07		
1855			-
1855		69.83	
3630	39.45		

NOTE: not scaled to sea level conditions

CHARGE WEIGHT: 111,039 pounds TNT equivalent

CASE WEIGHT: 21,060 pounds
STRUCTURE WEIGHT: 5,000 pounds
COVER WEIGHT: 3,600,000 pounds

DATE: 18 December 1963
Barometric Pressure: 935.0 mbar (13.56 psi)
Temperature: 57.6°F

GAUGE TYPE: BRL Self-Recording

DONOR: 2,106 cans of Comp B

REFERENCE: NOTS TP 3843

ESKIMO I

RANGE (ft)	PRESSURE (psi)		
	FRONT	SIDE	REAR/rear quarter
410	12		
410			7.45
526	7.86		
526			5.71
526		6.05	
703			4.08
703		4.54	
880	3.02		
880			2.6
880		3.31	
1580	1.47		
1580		-	
2690	0.75		
2690		0.89	

NOTE: not scaled to sea level conditions

RANGE (ft)	IMPULSE (psi-ms)		
	FRONT	SIDE	REAR/rear quarter
410	530		
410			248
526	418		
526			252
526		292	
703			194
703		250	
880	216		
880			154
880		229	
1580	152		
1580		-	
2690	107		
2690		78	

NOTE: not scaled to sea level conditions

CHARGE WEIGHT: 200,000 pounds TNT

CASE WEIGHT: 1,159,000 pounds
STRUCTURE WEIGHT: 5,000 pounds
COVER WEIGHT: 4,890,000 pounds

DATE: 8 December 1971
Barometric Pressure: 936.0 mbar (13.58 psi)
Temperature: 55°F

GAUGE TYPE: BRL Self-Recording

DONOR: 13,696 155-mm TNT-loaded projectiles

REFERENCE: NWC TP 5430

ESKIMO III

RANGE (ft)	PRESSURE (psi)		
	FRONT	SIDE	REAR/rear quarter
660.00	10.80		
660.00	10.40		
660.00		8.06	
660.00		8.35	
660.00			6.34
660.00			5.50
1320.00	2.20		
1320.00	2.88		
1320.00		3.30	
1320.00		3.60	
1320.00			2.40
1320.00			1.80
2115.00	1.28		
2115.00	1.48		
2115.00		1.60	
2115.00		1.21	
2630.00	0.75		
2630.00	0.80		
2630.00		1.27	
2630.00		1.15	
3526.00		0.88	
3526.00		0.41	

NOTE: not scaled to sea level conditions

RANGE (ft)	IMPULSE (psi-ms)		
	FRONT	SIDE	REAR/rear quarter
660.00	515.93		
660.00	529.68		
660.00		428.65	
660.00		435.30	
660.00			-
660.00			-
1320.00	-		
1320.00	223.68		
1320.00		-	
1320.00		-	
1320.00			187.74
1320.00			-
2115.00	136.33		
2115.00	172.10		
2115.00		-	
2115.00		112.03	
2630.00	55.70		
2630.00	-		
2630.00		149.32	
2630.00		80.96	
3526.00		20.35	
3526.00		-	

NOTE: not scaled to sea level conditions

CHARGE WEIGHT: 374,406 pounds TNT equivalent

CASE WEIGHT: 337,100 pounds
STRUCTURE WEIGHT: 5,000 pounds
COVER WEIGHT: 6,550,000 pounds

DATE: 12 June 1974
Barometric Pressure: 936.0 mbar (13.58 psi) (est)
Temperature: 85°F (est)

GAUGE TYPE: BRL Self-Recording

DONOR: 916 M117 TRITONAL-loaded bombs

REFERENCE: NWC TP 5771

ESKIMO VI

RANGE (ft)	PRESSURE (psi)		
	FRONT	SIDE	REAR/rear quarter
210.00	36.00		
210.00		17.80	
210.00			14.20
530.00	5.30		
530.00		3.75	
530.00			3.10
880.00	2.20		
880.00		-	
880.00			1.60
1760.00	0.35		
1760.00		0.45	
1760.00			0.26

NOTE: not scaled to sea level conditions

RANGE (ft)	IMPULSE (psi-ms)		
	FRONT	SIDE	REAR/rear quarter
210.00	613.00		
210.00		300.00	
210.00			270.00
530.00	185.00		
530.00		121.00	
530.00			115.00
880.00	25.50		
880.00		-	
880.00			[illegible]
1760.00	23.59		
1760.00		30.56	
1760.00			15.24

NOTE: not scaled to sea level conditions

CHARGE WEIGHT: 51,300 pounds TNT equivalent

CASE WEIGHT: 31,200 pounds
STRUCTURE WEIGHT: 2,000 pounds
COVER WEIGHT: 1,015,000 pounds

DATE: 23 July 1980
Barometric Pressure: 936.0 mbar (13.58 psi) (est)
Temperature: 85°F (est)

GAUGE TYPE: BRL Self-Recording & piezoresistive

DONOR: 60 MK 16 HBX-3-loaded torpedoes

REFERENCE: NCEL TR 889

HASTINGS IGLOO AIRBLAST

CHARGE WEIGHT (pounds)	CHARGE POSITION* (feet)	GAUGE POSITION** (feet)	PEAK PRESSURE (psi)	POSITIVE IMPULSE (psi-ms)
24	13	80F	0.5	
		90F	0.4	
		60S	0.76	3.75
		90S	0.55	2.59
100	40	60F	1	9.85
		90F	0.7	7.78
		50S	1.2	8.55
		90S	0.74	4.11
150	40	60F	1.41	13.46
		90F	1.23	9.94
		50S	1.53	8.83
		90S	1.07	7.21
12	13	60F	0.4	4.69
12	13	60F	0.62	4.83
		90F	0.46	3.27
		50S	0.67	5.52
		90S	0.34	3.06
12	67	60F	0.16	0.53
		90F	0.25	1.73
		50S	0.39	1.91
		90S	0.23	1.10
12	67	60F	0.36	2.87
		90F	0.33	1.05
		50S	0.69	2.37
		90S	0.27	1.05
16	13	60F	0.49	4.03
		90F	0.34	2.50
		50S	0.51	3.24
		90S	0.35	2.36

*Distance measured from headwall to charge location inside igloo
**Distance measured from center of headwall to where gauge located
F = in front of headwall
S = to side of headwall

CHARGE WEIGHT: see table

CASE WEIGHT: 0
STRUCTURE WEIGHT: unknown
COVER WEIGHT: unknown

DATE: 1984
Barometric Pressure: unknown (sea level assumed)
Temperature: unknown (standard assumed)

GAUGE TYPE: piezoelectric

DONOR: TNT blocks

REFERENCE: ARBRL-MR-03356

MK 82 BUFFERED STORAGE 1

RANGE (feet)	PRESSURE (psi)		
	FRONT	SIDE	REAR
550	2.14	3.54	
900		1.56	
1200	1.15		
1500	0.62	0.93	
1600	0.64	0.81	

NOTE: not scaled to sea level conditions

RANGE (feet)	POSITIVE IMPULSE (psi-ms)		
	FRONT	SIDE	REAR
550	36.79	96.90	
900			
1200	36.96		
1500	38.99	43.49	
1600	24.33	36.01	

NOTE: not scaled to sea level conditions

CHARGE WEIGHT: 36,600 pounds TNT

DATE: 2/5/87
Barometric Pressure: 25.87" Hg
Temperature: 46°F

DONOR: 180 MK82 bombs–TRITONAL loaded
34,560 pounds TRITONAL

STRUCTURE: IGLOO BUNKER

MK 82 BUFFERED STORAGE 2

RANGE (feet)	PRESSURE (psi)		
	FRONT	SIDE	REAR
550	3.62	4.51	
900	1.56		
900	1.56	2.35	
1200	1.12	1.36	
1200	1.16	1.35	
1650	1.02	0.93	
1650	0.83	0.91	

NOTE: not scaled to sea level conditions

RANGE (feet)	POSITIVE IMPULSE (psi-ms)		
	FRONT	SIDE	REAR
550	187.63	180.05	
900	104.59		
900	102.95	122.54	
1200	82.43	78.09	
1200	83.65	83.73	
1650	85.79	62.95	
1650	61.62	47.76	

NOTE: not scaled to sea level conditions

CHARGE WEIGHT: 54,890 pounds TNT

DATE: 5/7/87
Barometric Pressure: 25.86" Hg
Temperature: 80°F

DONOR: 270 MK 82 bombs–TRITONAL loaded
51,840 pounds TRITONAL

STRUCTURE: IGLOO BUNKER

MK 82 BUFFERED STORAGE 3

RANGE (feet)	PRESSURE (psi)		
	FRONT	SIDE	REAR
200	11.73	8.83	
200		10.67	
400	7.19	4.93	
400	5.75		
550		3.38	
550	3.50		
900	1.95	2.15	
900	1.70	1.64	
1200	1.06		
1200	1.09	1.29	

NOTE: not scaled to sea level conditions

RANGE (feet)	POSITIVE IMPULSE (psi-ms)		
	FRONT	SIDE	REAR
200	333.16	401.59	
200		229.68	
400	341.45	160.72	
400			
550		130.86	
550	242.14		
900		92.49	
900	95.75	83.76	
1200	68.25		
1200	77.02	64.40	

NOTE: not scaled to sea level conditions

CHARGE WEIGHT: 63,430 pounds TNT

DATE: 11/4/87
Barometric Pressure: 25.96" Hg
Temperature: 52°F

DONOR: 312 MK 82 bombs--TRITONAL loaded
59,904 pounds TRITONAL

STRUCTURE: IGLOO BUNKER

MK 82 BUFFERED STORAGE 4

RANGE (feet)	PRESSURE (psi)		
	FRONT	SIDE	REAR
200	21.4	18.1	
200		19.9	
400	8.21	4.67	
400		4.96	
550	4.57	4.51	
550	4.03	4.32	
900	2.06	2.06	
900	3.26	1.73	
1200		1.38	
1200	1.31	1.64	

NOTE: not scaled to sea level conditions

RANGE (feet)	POSITIVE IMPULSE (psi-ms)		
	FRONT	SIDE	REAR
200	135.90	233.70	
200		165.20	
400	153.40	155.30	
400		168.30	
550	108.00	90.80	
550	150.80	114.20	
900	184.00	90.20	
900	144.60	77.30	
1200		75.50	
1200	75.80	135.90	

NOTE: not scaled to sea level conditions

CHARGE WEIGHT: 63,430 pounds TNT

DATE: 12/16/87
Barometric Pressure: 22.24" Hg
Temperature: 27°F

DONOR: 312 MK 82 bombs–TRITONAL loaded
59,904 pounds TRITONAL

STRUCTURE: IGLOO BUNKER

MK 84 TEST 13

RANGE (feet)	PRESSURE (psi)		
	FRONT	SIDE	REAR
431	14.13	11.25	
431	14.5	10.94	
707		4.7	
707	5.94	4.9	
1178	2.18	2.15	
1178	2.16	1.9	
1570	1.38		
1570	0.96	1.40	
1963	0.88	0.98	
1963	0.35	1.10	
2198	0.74	0.86	
2198	0.74	0.88	

NOTE: not scaled to sea level conditions

RANGE (feet)	POSITIVE IMPULSE (psi-ms)		
	FRONT	SIDE	REAR
431	613.00	413.00	
431	662.00	420.00	
707		259.00	
707	288.00	256.00	
1178	164.00	148.00	
1178	145.00	119.00	
1570	114.00		
1570	78.00	118.00	
1963	88.00	88.50	
1963	32.50	99.50	
2198	80.00	81.30	
2198	80.00	83.80	

NOTE: not scaled to sea level conditions

CHARGE WEIGHT: 129,430 pounds TNT

DATE: 8/29/86
Barometric Pressure: 25.1" Hg
Temperature: 84°F

DONOR: 128 MK 84 bombs–TRITONAL loaded
120,960 pounds TRITONAL

STRUCTURE: EARTH COVERED CONCRETE
ARCH IGLOO

MK 84 TEST 15

RANGE (feet)	PRESSURE (psi)		
	FRONT	SIDE	REAR
550	4.47	5.01	
900	2.12		
900	2.5	3.1	
1200	1.12	1.39	
1200	1.26	1.66	
1500	1.07	1.33	
1500	1.13	1.21	
1650	0.97	1.15	
1650		1.11	

NOTE: not scaled to sea level conditions

RANGE (feet)	POSITIVE IMPULSE (psi-ms)		
	FRONT	SIDE	REAR
550	179.20	197.60	
900			
900		164.40	
1200	86.50		
1200	83.02	91.57	
1500	82.30	104.80	
1500	97.70	89.10	
1650	89.67	90.90	
1650		83.72	

NOTE: not scaled to sea level conditions

CHARGE WEIGHT: 96,620 pounds TNT

DATE: 11/14/86
Barometric Pressure: 25.15" Hg
Temperature: 58°F

DONOR: 96 MK 84 bombs–TRITONAL loaded
90,720 pounds TRITONAL

STRUCTURE: SIMULATED EARTH COVERED IGLOO

MK 84 TEST 17

RANGE (feet)	PRESSURE (psi)		
	FRONT	SIDE	REAR
550	4.05	3.9	
550	4.17	3.6	
900	1.95	1.7	
900	1.9	1.83	
1200	1.45	1.32	
1200	1.27	1.34	
1650	0.78	0.7	
1650	0.90	0.72	

NOTE: not scaled to sea level conditions

RANGE (feet)	POSITIVE IMPULSE (psi-ms)		
	FRONT	SIDE	REAR
550	157.00	146.00	
550	168.00	142.80	
900	90.49	84.48	
900	94.11	85.00	
1200	79.00	69.00	
1200	49.00	72.12	
1650	50.23	48.68	
1650	49.68	44.00	

NOTE: not scaled to sea level conditions

CHARGE WEIGHT: 48,535 pounds TNT

DATE: 6/24/87
Barometric Pressure: 25.20" Hg
Temperature: 76°F

DONOR: 48 MK 84 bombs–TRITONAL loaded
45,360 pounds TRITONAL

STRUCTURE: SIMULATED EARTH COVERED IGLOO

MK 84 TEST 18

RANGE (feet)	PRESSURE (psi)		
	FRONT	SIDE	REAR
200	23.4	17.1	
200		19	
400	8.35	6.65	
400		7.26	
550	5.34	4.69	
550	5.16	4.6	
900	2.35	1.96	
900		1.89	
1200	1.98	1.43	
1200	1.77	1.59	

NOTE: not scaled to sea level conditions

RANGE (feet)	POSITIVE IMPULSE (psi-ms)		
	FRONT	SIDE	REAR
200			
200			
400	262.00	206.90	
400		227.60	
550	197.20	172.50	
550	267.30	170.00	
900	128.50	139.10	
900		143.70	
1200	96.23	89.27	
1200	111.50	87.89	

NOTE: not scaled to sea level conditions

CHARGE WEIGHT: 64,714 pounds TNT

DATE: 8/12/87
Barometric Pressure: 25.68" Hg
Temperature: 71°F

DONOR: 64 MK 84 bombs--TRITONAL loaded
60,480 pounds TRITONAL

STRUCTURE: SIMULATED EARTH COVERED IGLOO

MK 84 TEST 19

RANGE (feet)	PRESSURE (psi)		
	FRONT	SIDE	REAR
200	22.26	14.52	
200	25.02	14.32	
400	8.27	7.13	
400	6.9	5.92	
550	4.61	3.99	
550	4.14	3.77	
900	2.28	1.53	
900	2.08	2.00	
1200	1.46	1.67	
1200	1.45	1.02	

NOTE: not scaled to sea level conditions

RANGE (feet)	POSITIVE IMPULSE (psi-ms)		
	FRONT	SIDE	REAR
200		463.40	
200	366.50	268.60	
400	276.50	224.00	
400		197.50	
550	167.00	150.00	
550	140.00	134.20	
900	100.40	38.20	
900	39.50	106.40	
1200	75.10	88.40	
1200	83.10	40.30	

NOTE: not scaled to sea level conditions

CHARGE WEIGHT: 64,714 pounds TNT

DATE: 9/23/87
Barometric Pressure: 25.90" Hg
Temperature: 65°F

DONOR: 64 MK 84 bombs–TRITONAL loaded
60,480 pounds TRITONAL

STRUCTURE: SIMULATED EARTH COVERED IGLOO

MODULAR IGLOO

RANGE (feet)	PRESSURE (psi)		
	FRONT	SIDE	REAR
476	13.70	14.40	8.42
873	4.60	8.80	4.00
1429	3.10	3.12	
2381	1.08	0.99	1.06
3969	0.61	0.71	0.56
4445	0.28	0.36	0.49

NOTE: not scaled to sea level conditions

RANGE (feet)	POSITIVE IMPULSE (psi-ms)		
	FRONT	SIDE	REAR
476		281.00	344.00
873	156.70	322.00	
1429	109.30	111.00	
2381	46.20	39.80	45.00
3969	34.60	33.00	23.80
4445	19.60	16.70	22.70

NOTE: not scaled to sea level conditions

CHARGE WEIGHT: 500,000 pounds TNT

DATE: 11/18/88
Barometric Pressure: 873.9 mbar
Temperature: 2.9 °C

DONOR: 450,450 pounds flake COMPOSITION B

STRUCTURE: MODULAR IGLOO

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4. TITLE AND SUBTITLE
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12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The airblast and fragmentation produced by explosions inside earth-covered explosive storage structures (IGLOOS or bunkers) have been reexamined and assembled into one document. The data were examined with the following questions in mind: (1) How do they compare with current Department of Defense Standards? (2) Can the data be scaled to produce general empirically-derived prediction equations? (3) Do the structures tested during the Air Force Buffered Storage Test Program come from the same data family? These goals were met. Generalized prediction equations (with confidence limits) are provided for airblast. It was discovered that there is a major deficiency in the data relating to the debris/fragmentation produced by explosions in such structures.

14. SUBJECT TERMS

ESKIMO TESTS	IGLOO	Explosive Safety
Earth-covered Magazines	Safety Standards	Airblast
Fragmentation	Debris	

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16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
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